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CHEMISTRY 30

MODULE 6: THE NATURE OF ACIDS AND BASES



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Chemistry 30

Module 6

The Nature of Acids and Bases



**Distance
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Alberta

EDUCATION

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Chemistry 30
 Student Module
 Module 6
 The Nature of Acids and Bases
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Welcome to Module 6!

We hope you'll enjoy your study of *The Nature of Acids and Bases*. Remember, to make your learning a bit easier, several videocassettes are referred to throughout the modules. Your textbook *Nelson Chemistry* will also enhance your studies.



COURSE OVERVIEW

This course contains seven modules. The module you are working in is highlighted in deeper colour. It is recommended that you work through the modules in the order given since several concepts build on each other as you progress in the course.

CHEMISTRY 30



Module 1
Exploring Energy's Mysteries



Module 2
Putting Energy to Work



Module 3
Electrochemistry – Give and Take



Module 4
The Practical Side of Redox



Module 5
Chemistry in Balance



Module 6
The Nature of Acids and Bases



Module 7
Acid-Base Applications

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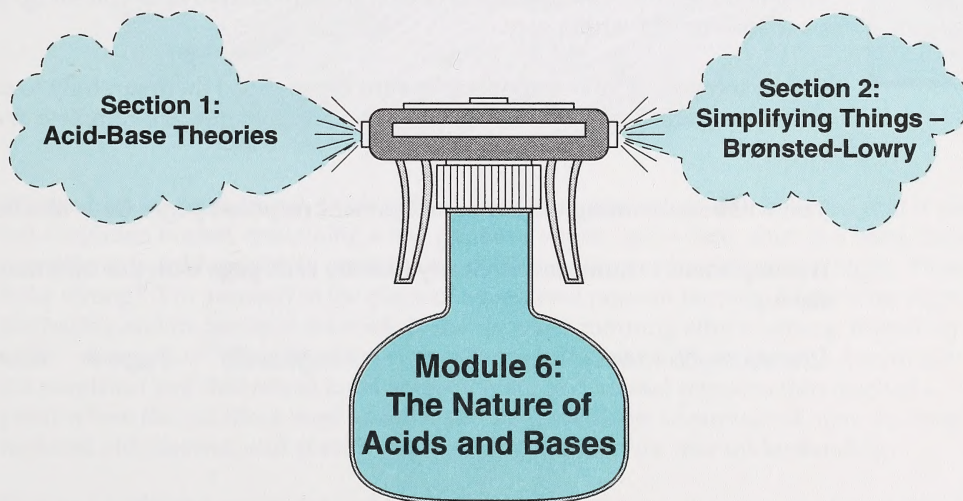
<https://archive.org/details/chemistry3006albe>

MODULE OVERVIEW

ubiq•ui•tous \yü-'bik-wät-əs\ *adj.* (1837): existing or being everywhere at the same time; constantly encountered; WIDESPREAD — **ubiq•ui•tous•ly** *adv* — **ubiq•ui•tous•ness** *n*

How's that for a new word? Ubiquitous certainly describes acids and bases! Even if you don't know what acids or bases are, you have to know where they are – they are everywhere! For example, the atmosphere of the planet Venus is so acidic that space probes can only transmit information back to Earth for about an hour before they are destroyed, yet a lemon is acidic and can be eaten without harm. The alkali salt flats of Utah are so laden with basic solutes that nothing can grow there. Yet, a slightly basic solution called blood runs through your veins and arteries. Your stomach juices are acidic; your intestinal juices are basic. The tap water you drink, and the foods you eat are either acidic or basic. Since acids and bases are so incredibly ubiquitous, it is extremely important that you learn everything you can about them.

In this module, you will learn how society has come to its present knowledge and understanding of acids and bases. One of the most powerful theories of acids and bases will be used to explain the behaviour of an amazing group of acids known as indicators.



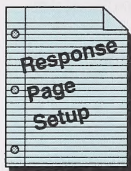
Evaluation

Your mark in this module will be determined by how well you complete the assignments at the end of each section. You must complete all assignments. In this module you are expected to complete three assignments. The mark distribution is as follows:

Section 1 Assignment	25 marks
Section 2 Assignment	40 marks
Final Module Assignment	<u>35 marks</u>
TOTAL	100 marks

When doing your assignments, work slowly and carefully. If you are having difficulties, go back and review the appropriate section.

Read all parts of your assignment carefully. Plan and do your rough work on your own paper. Revise and edit your responses; then set up your final copy for submission on your own paper. Lined looseleaf is recommended. Make sure your answers are neat and organized, with wide left margins and space for teacher comments after each assignment.



When you see this icon, ideas and details are provided to help you set up and organize your answer in a certain way.

Before submitting your responses, be sure to proofread them carefully to ensure they say what you want, that they are neat and clear, and that they are complete and missing no material.

You will be submitting **only** your **assignment response pages** for evaluation.

It is important to number and clearly identify each page with this information placed at the top.

Chemistry 30 – Module 6 Section # Assignment Page # Name and ID #

SECTION

1

Acid-Base Theories



Where do mice come from? During the dark ages, it was commonly believed that if you left a wooden bucket, containing a few grains of wheat, and a dirty shirt in a barn, these ingredients would magically combine to spontaneously produce mice overnight. Were folks wrong? Put yourself in the place of a medieval peasant farmer. Night after night, the bucket and its contents were left in the barn and morning after morning, there they were – more mice! What would you have thought, based on the evidence? Eventually the empirical and theoretical knowledge of plant and animal reproduction reached a point where the old ideas were abandoned. As knowledge accumulated, new theories replaced old theories, and at each step society got closer to a true understanding.

Section 1 is about a search for understanding. You will learn about some of the earliest theories of acids and bases, and about how each explanation could account for only some acid and base behaviour. You will then review the relationship between the solvent water and the properties of acids and bases. You will see how a scientific theory must be continually modified or changed to explain new evidence and eliminate contradictions. Finally, you will examine the desired characteristics that a working theory must possess in order to be considered successful.

ACTIVITY

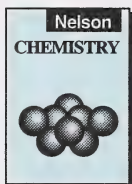
1

The Scientific Process in Action

Have you ever thought you had something completely figured out only to find out you were completely wrong?



Scientists have been in this situation countless times, but they never stopped trying!



Most early theories focused on acid behaviour and ignored bases. Read the first half of page 461 of your textbook (to the end of Davy's theory) to learn more about these early theories.

1. Use a chart similar to the following to summarize the important ideas of the two theories presented.

Scientist	Theory	Main Feature of Theory	Reason Theory Was Discarded
Antoine Lavoisier	Oxygen Theory		
Sir Humphry Davy and Justus von Liebig	Hydrogen Theory		

Check your answers by turning to the Appendix, Section 1: Activity 1.

The Theory Parade Begins



THE BETTMANN ARCHIVE

Antoine Lavoisier

↓ proposed

The Oxygen Theory

but,

- Not all oxides produce acids.
- Some acids don't contain oxygen.

try
again →



THE BETTMANN ARCHIVE

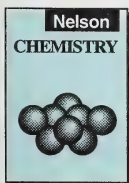
Sir Humphry Davy

↓ proposed

The Hydrogen Theory

but,

- Many hydrogen-containing compounds are neutral.



Another early theory, known as the Arrhenius theory of acids and bases, did have some success explaining acid and base behaviours. This theory was discussed in some detail in the Chemistry 20 course and you examined it briefly in Module 5. To review, carefully read page 117 of your textbook. Make a special note of Table 5.1. Then, read the paragraph about Arrhenius's theory on page 461 and answer the following questions.

2. a. Write a definition of a base according to the Arrhenius theory.
- b. Write a definition of an acid according to the Arrhenius theory.



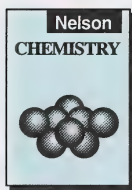
THE BETTMANN ARCHIVE

Svante Arrhenius

3. What role did Arrhenius believe water played in his theory?
4. How would Arrhenius describe the process of neutralization?
5. How would Arrhenius have defined a neutral solution?
6. Write balanced dissociation equations showing how each of the following substances would behave when dissolved in water according to the Arrhenius theory.
 - a. $\text{HCl}_{(\text{aq})}$
 - b. $\text{HNO}_{3(\text{aq})}$
 - c. $\text{KOH}_{(\text{aq})}$
 - d. $\text{CH}_3\text{COOH}_{(\text{aq})}$
 - e. $\text{Ba}(\text{OH})_{2(\text{aq})}$
7. How did the Arrhenius definition distinguish between neutral solutions that were electrolytes and those that were non-electrolytes?

Check your answers by turning to the Appendix, Section 1: Activity 1.

Have you ever predicted an event before it happened? A successful theory can do that every time! How successful is the Arrhenius theory at predicting whether a substance will produce an aqueous solution that is acidic, basic, or neutral? The following investigation will help to answer this question.



Investigation 15.1: Testing Arrhenius's Acid-Base Definitions

Perform Investigation 15.1 as described on page 462 of your textbook. Carefully follow the directions given for this investigation. Pay special attention to the required components, safety aspects, and applied science skills.

Science Skills

- ☒ A. Initiating
- ☒ B. Collecting
- ☒ C. Organizing
- ☒ D. Analysing
- ☐ E. Synthesizing
- ☒ F. Evaluating

Caution

Important Note – Disposal Information

Any chemicals used in investigations in this module should not be poured down the sink unless otherwise indicated. Keep waste materials in closed, labelled containers. Contact your nearest high school or fire department for disposal information.

Guidelines

- Use a spot plate on which to do your solution testing. Use about 15-20 drops of solution per spot.
 - All of the solutions used in this investigation conduct electricity. If you have access to a conductivity tester, you can confirm this statement. You can also use your multimeter to confirm the conductivity.
 - Aqueous sulphur dioxide will be substituted with aqueous carbon dioxide. You can use carbonated water (or any clear, colourless soft drink) to provide the $\text{CO}_{2(\text{aq})}$.
8. Using only the Arrhenius definition for acids and bases, fill in the given chart and predict whether the following substances will be acidic, basic, or neutral in aqueous solution.

Substance in Solution (0.10 mol/L)	Chemical Formula	Form in Solution	Prediction (acid, base, neutral)
hydrogen chloride			
sodium carbonate (soda ash)			
sodium hydrogen carbonate			
sodium hydrogen sulphate			
sodium hydroxide (lye)			
calcium hydroxide (saturated)			
carbon dioxide			
magnesium oxide (saturated)			
ammonia			
hydrogen acetate (vinegar)			
water			

9. Write an experimental design for this investigation. Include the manipulated, responding, and controlled variables.
10. Write a procedure that will enable you to classify each of the substances in solution as acidic, basic, or neutral.
11. Construct an evidence table, perform your procedure, and record your results.

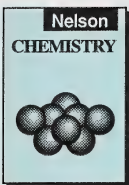
12. To assist you in your analysis, summarize the evidence from your data table and your predictions from your prediction chart on a table similar to the following:

SUMMARY DATA TABLE

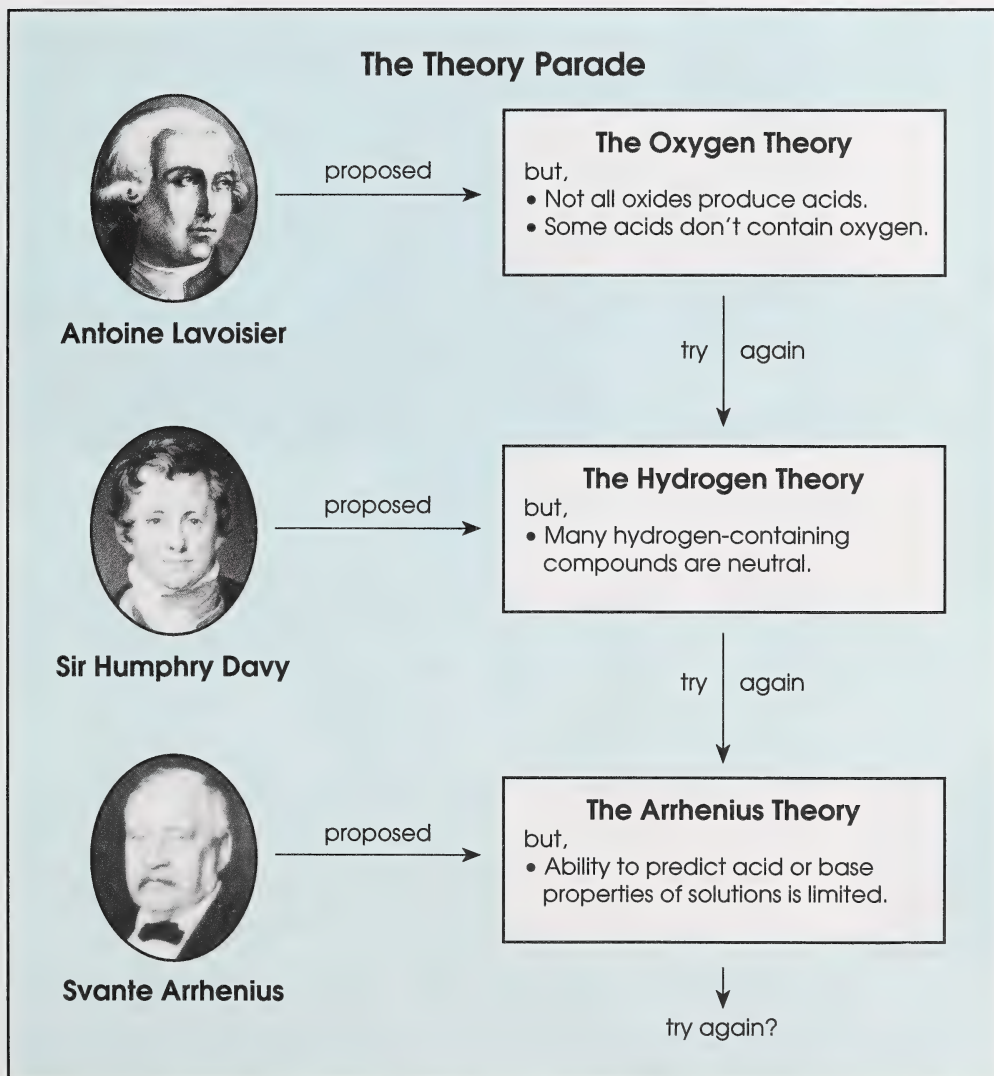
Substance in Solution (0.10 mol/L)	Electrolyte (Yes or No)	Predicted Property	Actual Property
hydrogen chloride			
sodium carbonate (soda ash)			
sodium hydrogen carbonate			
sodium hydrogen sulphate			
sodium hydroxide (lye)			
calcium hydroxide (saturated)			
carbon dioxide			
magnesium oxide (saturated)			
ammonia			
hydrogen acetate (vinegar)			
water			

13. Use your Summary Data Table to answer the following:
- How many substances did the Arrhenius theory predict would be acidic?
 - How many substances actually tested acidic?
 - How many substances did the Arrhenius theory predict would be neutral?
 - How many substances were actually neutral?
 - How many substances did the Arrhenius theory predict would be basic?
 - How many substances actually tested basic?
14. Are there any common features shared by those substances that it failed to predict properly? Can you draw any conclusions from this information?
15. According to your data does a substance have to be an electrolyte (produces a conducting solution) in order to be an acid or a base?

16. Based on your data, what conclusion can you draw about how successful the Arrhenius theory is at predicting the acidic or basic properties of substances in solution? Explain your answer completely.
17. Turn to page 497 of your textbook, and do review questions 1 (omit the Brønsted-Lowry definition), 2, and 3.



Check your answers by turning to the Appendix, Section 1: Activity 1.



PHOTOS FROM THE BETTMANN ARCHIVE

In this activity you discovered that the path to understanding is not necessarily a smooth one. You have seen that the first few halting steps towards the understanding of acids and bases were really more like two steps forward and one step back. But no matter how slow, progress was always in the forward direction.

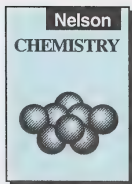
ACTIVITY

2 Was Arrhenius Wrong?



Is it possible to be partially correct and partially wrong? Of course! The tricky part is recognizing the part that is wrong and trying to correct it.

Although the Arrhenius theory or definition was successful at explaining some acid and base behaviours, it failed to predict the acid or base behaviour of a number of substances. It needed to be revised. The Arrhenius theory gave water no role to play other than to provide a passive medium in which free hydrogen ions and free hydroxide ions could exist. Scientists began to wonder if perhaps water might have a more active role in acid-base theory.



Read from page 462 to the middle of 463 in your textbook; then, answer the following questions.

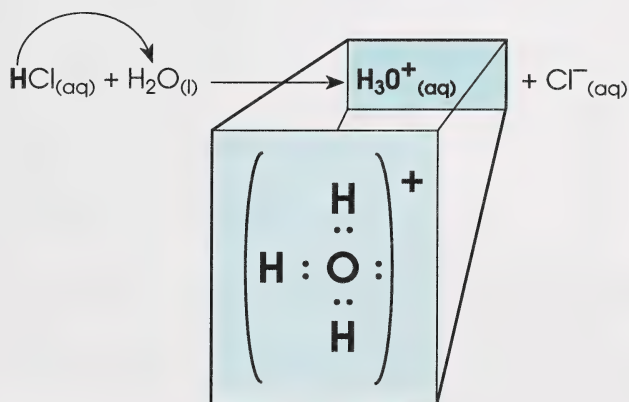
1. Describe two characteristics of a good theory.
2. What two key ideas led to a revision of the Arrhenius theory?
3. Is there any evidence that hydrogen ions can exist free in solution?
4. What feature of the hydrogen ion makes it highly unlikely that it can exist as a free proton in solution?

- What characteristic does water possess that makes it likely to attract hydrogen ions to it?
- Since free hydrogen ions do not exist in solution, what particle has been proposed as an alternative to free hydrogen ions?

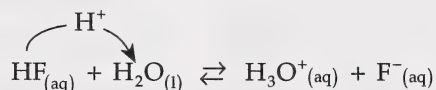
Check your answers by turning to the Appendix, Section 1: Activity 2.

hydronium ion –
a hydrated
hydrogen ion

It is thought that a **hydronium ion** forms when a hydrogen ion ($\text{H}^+_{(\text{aq})}$) from an acid bonds to a water molecule. The water molecule now has something to do rather than being only a solvent. The following diagram illustrates how a hydrogen ion transfers from the acid to the water molecule and forms the hydronium ion.



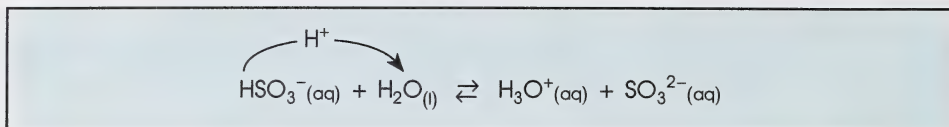
Proton (or hydrogen ion) transfer reactions are a new concept and will need some practice to get used to. In the reaction



the positively charged hydrogen ion transfers from the neutral $\text{HF}_{(\text{aq})}$ molecule to a neutral water molecule. This *travelling positive charge* does two things:

- It makes the particle to which it attaches more positive. In this case $\text{H}_2\text{O}_{(\text{l})}$ becomes $\text{H}_3\text{O}^+_{(\text{aq})}$.
- It makes the particle it leaves behind more negative (or less positive if you like). That is why the neutral $\text{HF}_{(\text{aq})}$ becomes negatively charged $\text{F}^-_{(\text{aq})}$ on the product side of the equation.

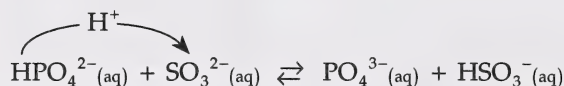
7. Here is another example that illustrates hydrogen ion transfer.



Fill in the blanks in the following sentences which describe the effects of hydrogen ion transfer in the given example system.

The hydrogen ion transfers from the _____ ion to the _____ molecule. The water molecule _____ (loses/gains) a _____ (positive/negative) charge to become a _____ ion. As the H^+ leaves, the $\text{HSO}_3^-(\text{aq})$ ion _____ (loses/gains) a _____ (positive/negative) charge to become a _____ ion.

It is not necessary that the water molecules be a reactant in a proton (hydrogen ion) transfer reaction. Other substances can also accept transferred hydrogen ions. In the reaction

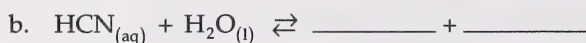


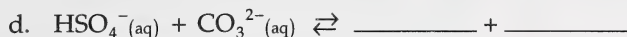
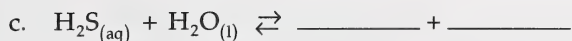
the hydrogen ion transfers from the $\text{HPO}_4^{2-}(\text{aq})$ ion to a $\text{SO}_3^{2-}(\text{aq})$ ion.

Use this example to fill in the blanks in the following sentences.

8. During this hydrogen ion transfer, the sulphite ion _____ (loses/gains) a _____ (positive/negative) charge to become a _____ ion. When the H^+ ion leaves, the $\text{HPO}_4^{2-}(\text{aq})$ ion _____ (gains/loses) a _____ (positive/negative) charge to become a _____ ion.
9. Indicate the following for each of the given reactions:

- Draw an arched arrow as in the preceding examples to indicate the direction of the hydrogen ion transfer.
- Predict the formulas of the product particles and their charges.





10. Considering your reading on page 463 of *Nelson Chemistry*, what evidence is there for the existence of hydronium ions in solution?

Check your answers by turning to the Appendix, Section 1: Activity 2.

You have now seen that the concept of a hydronium ion replaced the idea of a free hydrogen ion. How did this improve the Arrhenius theory?

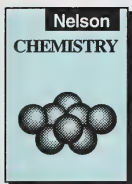
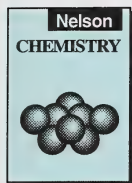
It is important for you to remember that a good theory can both explain existing evidence and predict the results of new experiments. Does the modification of the Arrhenius theory help you to explain or predict? To find out, read from the middle of page 463 to the bottom of page 464 in *Nelson Chemistry* and answer the following questions.

- In a complete sentence, write the new definition of an acidic solution according to the modification of the Arrhenius theory or definition.
- Write a balanced equation to explain how nitric acid would react with water to form a hydronium ion.
- The Arrhenius theory would predict that sulphur dioxide ($\text{SO}_{2(\text{g})}$) is a neutral substance. However, environmental evidence such as depleted forests and other areas due to acid rain would tell you otherwise. As mentioned in your textbook, there is a two-step equation to explain the acidic solution formed by $\text{SO}_{2(\text{g})}$. Write out this two-step equation.

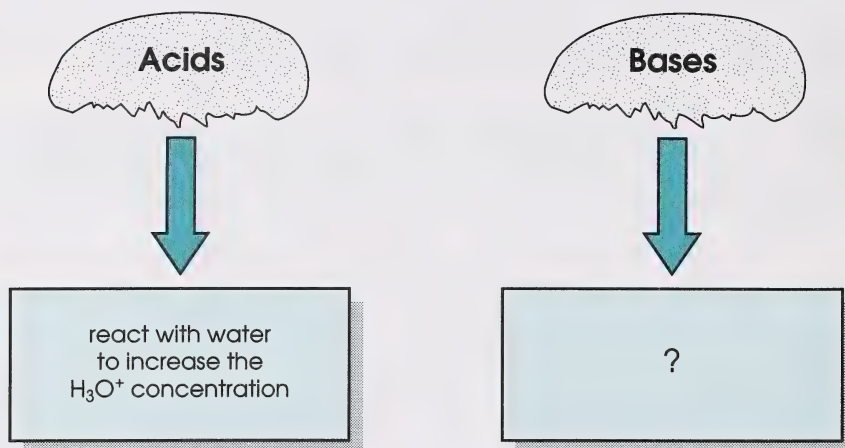


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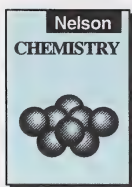
Check your answers by turning to the Appendix, Section 1: Activity 2.



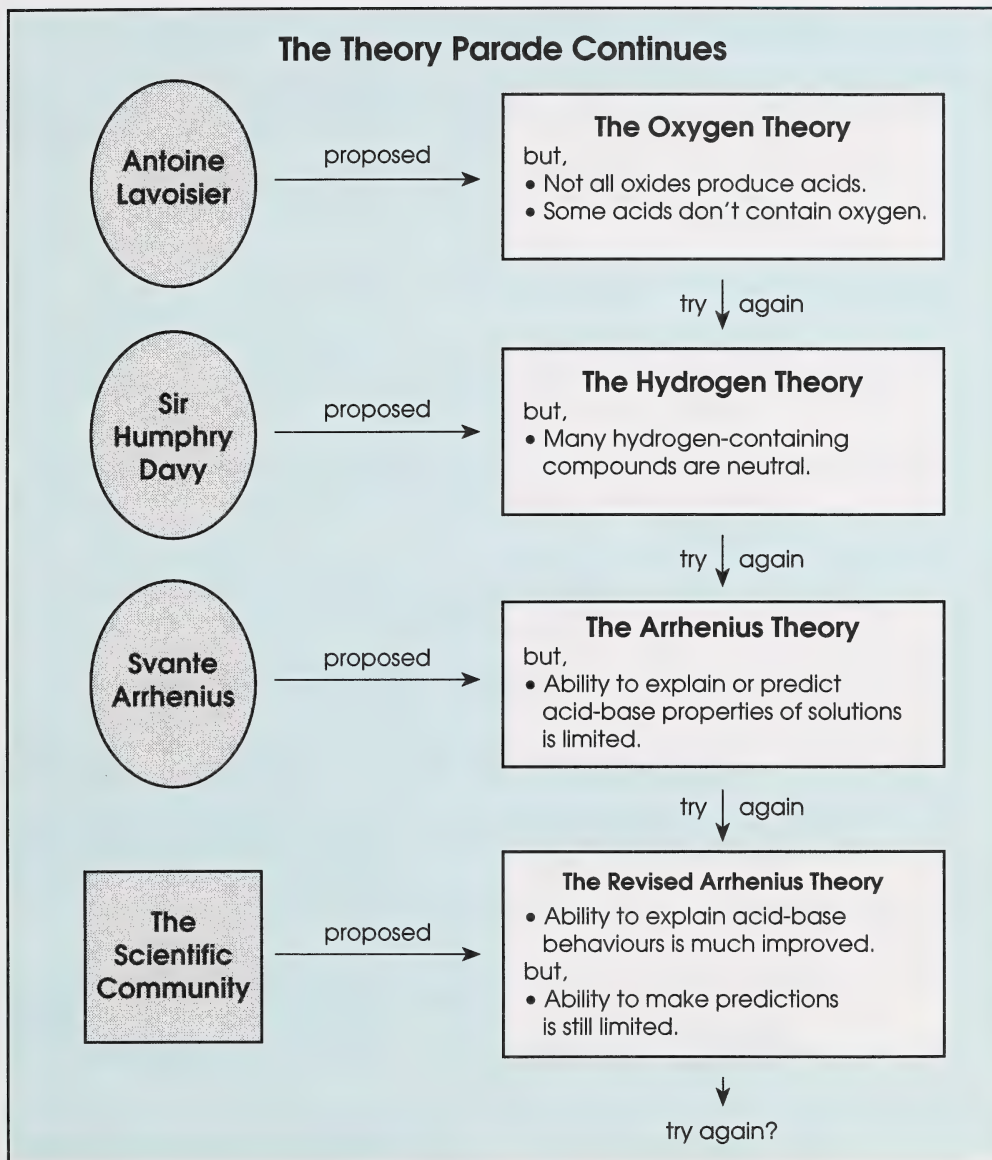
So far, you have mainly concentrated on acids. What about bases? What is their place in this modified theory?



14. Write the new definition for a basic solution, based on your reading.
15. Write an equation to explain how the hydrogen phosphate ion can react with water to produce a basic solution.
16. In Investigation 15.1 the Arrhenius theory predicted ammonia ($\text{NH}_{3(\text{aq})}$) would be neutral in solution, yet it tested basic in solution. Write a balanced equation to explain how $\text{NH}_{3(\text{aq})}$ forms a basic solution.
17. Would you say that your answers to the preceding three questions are explanations of existing base behaviour or predictions of results of new experiments? Explain.
18. Do textbook questions 1 and 2 on pages 464-465 of *Nelson Chemistry*.
19. Look at your answers to the preceding questions. Does the revision of the Arrhenius theory satisfy all the requirements of a good working theory? If not, where does it fall short?



Check your answers by turning to the Appendix, Section 1: Activity 2.



Do you need yet another theory? That depends on the answers to the following questions. Does the revision of Arrhenius's theory both explain and predict? Can it explain acid-base reactions that do not require a water medium? Some substances can act as an acid sometimes, and as a base at other times. Can the revised theory explain that? If a substance can act as either an acid or a base, will the revised theory predict what that substance will do under any given set of circumstances? The answer is *no* to all of these questions. The acid-base theory needs to be broadened even further. The parade is going to get longer!

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you have a clear understanding of the concepts, it is recommended that you do the Enrichment.

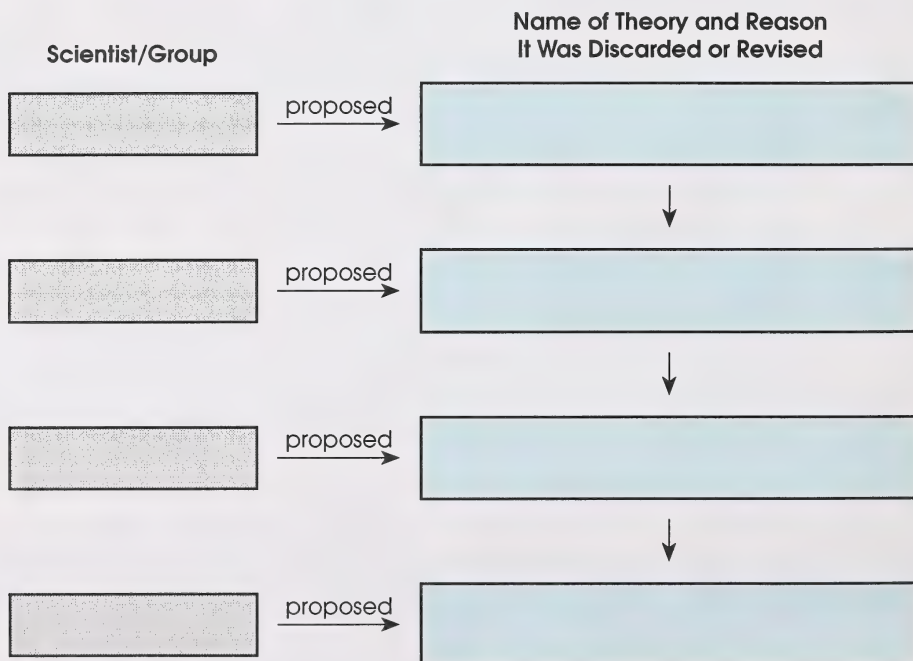
Extra Help

There are two main ideas put forward in this section.

- The growth of knowledge of acids and bases is an excellent example of the scientific process in action. Science process is the quest for knowledge, not the knowledge itself.
- The desired result of the search for knowledge through science process is a theory that will both explain empirical behaviours and predict the results of new experiments.

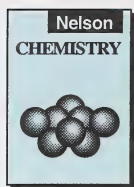
The journey from the earliest theories to the revision of Arrhenius's theory can be summarized in the following questions.

1. Find the information you need to fill in the following flow chart.



2. The following list consists of a number of statements which can be applied to the Arrhenius theory, the revised Arrhenius theory, or both theories. Identify each statement as follows: statements that apply only to the Arrhenius theory (A), those that apply only to the revised Arrhenius theory (RA), and statements that apply to both theories (B).
- A neutral solution has equal concentrations of $\text{H}^+_{(\text{aq})}$ and $\text{OH}^-_{(\text{aq})}$.
 - An acid contains $\text{H}_3\text{O}^+_{(\text{aq})}$ in solution.
 - A base dissociates to produce free $\text{OH}^-_{(\text{aq})}$ in solution.
 - The theory/theories can explain why $\text{NH}_{3(\text{g})}$ can produce a basic solution.
 - The theory/theories cannot predict whether $\text{H}_2\text{PO}_4^-_{(\text{aq})}$ will act as an acid or base.
 - Neutralization occurs when $\text{H}^+_{(\text{aq})} + \text{OH}^-_{(\text{aq})} \rightarrow \text{H}_2\text{O}_{(\text{l})}$.
 - The theory/theories involve(s) the creation of a hydronium ion.
 - Basic solutions are formed when substances react with water to produce hydroxide ions.
 - Water has no reactive role to play in the formation of acidic and basic solutions.
 - The theory/theories can only predict the basic behaviour of substances containing the hydroxide ion.
 - This theory can explain the acid or base behaviours of more substances than the other theory.
 - The theory/theories need(s) revision to improve the ability to predict new results.
 - A neutral solution has equal concentrations of $\text{H}_3\text{O}^+_{(\text{aq})}$ and $\text{OH}^-_{(\text{aq})}$.
3. Complete the following hydrogen ion transfer equations. Draw an arrow to indicate the direction of hydrogen ion transfer.
- $\text{H}_3\text{BO}_{3(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{_____} + \text{_____}$
 - $\text{HNO}_{3(\text{aq})} + \text{F}^-_{(\text{aq})} \rightleftharpoons \text{_____} + \text{_____}$

Check your answers by turning to the Appendix, Section 1: Extra Help.



If you would like further practice in working with the concepts presented in this section, answer any of questions 4, 5, 13, 14, 15, or 16 on pages 497-498 of your textbook. The answers to these questions can be found on pages 519-520 of *Nelson Chemistry*.

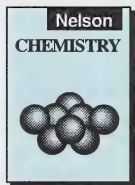
Enrichment

Complete **one** of the following questions.

1. Author and scientist Isaac Asimov, in his book *X Stands for Unknown*, said

Science is not a collection of results, abilities, or even explanations. Those are the products of science but are not science itself – any more than a table is carpentry, or standing at the finish line is racing. Science is a process, it is a way of thinking, a manner of approaching and possibly resolving problems, a route by which one can produce order and sense out of disorganization and chaotic observations. The true delight is in the finding out, rather than in the knowing.

Using your knowledge of the development of acid-base theory, write a one-page essay that discusses how this quotation illustrates the nature of science.



2. The article on page 465 of your textbook discusses the ideas of Sir Karl Popper, one of the world's greatest philosophers of science. Read the article carefully and then comment in paragraph form on the concepts of the following:
 - a. the principle of "testing by attempted falsification"
 - b. the application of this principle to the social sciences
 - c. the nature and role of criticism in social systems
3. Using the solutes in the following list, design and perform an experiment to test the ability of the revised Arrhenius theory to predict the acid-base properties of each solute. In your conclusion, compare the predictive abilities of the revised theory to those of the original Arrhenius theory.

List of solutes: Na_2HPO_4 , NH_3 , CH_3COOH , NaHSO_3 , and Na_2CO_3 .

Check your answers by turning to the Appendix, Section 1: Enrichment.

Conclusion

In this section you learned that the growth of knowledge of acids and bases is an excellent example of the scientific process in action and that science process is the quest for knowledge, not the knowledge itself. You studied a number of theories that were only partially successful in describing acid-base behaviour. You have also learned that the desired result of the search for knowledge through science process is a theory that will both explain empirical behaviours and predict the results of new experiments.



Sir Humphry Davy lectures at the Surrey Institute. (From an 1810 engraving.)

Section 1 Assignment: Acid-Base Theories

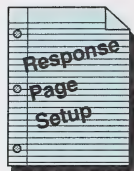
Review the Evaluation information found in the introductory pages of this module.

It is important to number and clearly identify each page with the following information at the top:

Chemistry 30 – Module 6 Section 1 Assignment Page # Name and ID#

Be sure to write legibly. Leave a wide left margin and number all of your pages.

Part A: Multiple Choice



Read each question carefully and decide which of the choices best completes the statement or answers the question. Place the number of each question in a vertical column and place your answer (A, B, C, or D) beside each number. Each question is worth one mark. (Total = 8 marks)

1. According to the Arrhenius theory, a base is defined as a species that dissociates in water to
 - A. decrease both the $[H^+_{(aq)}]$ and the $[OH^-_{(aq)}]$
 - B. increase both the $[H^+_{(aq)}]$ and the $[OH^-_{(aq)}]$
 - C. decrease the hydroxide ion concentration
 - D. increase the hydroxide ion concentration

2. According to Arrhenius, the substance that would be classified as an acid is
 - A. $CO_{2(aq)}$
 - B. $HCl_{(aq)}$
 - C. $HCO_3^-(aq)$
 - D. $HPO_4^{2-}(aq)$

Use the following information to answer the next six questions.

Match the letter of the appropriate acid-base theory to the descriptive statement to which it applies.

- A. Revision of the Arrhenius Theory
- B. Davy/Liebig Theory

- C. Arrhenius Theory
- D. Lavoisier Theory

3. An acid is a substance that ionizes in aqueous solution to produce $H^+_{(aq)}$ ions.
4. All acids contain oxygen.
5. An acid is a substance that reacts with water to produce hydronium ions.
6. Acids are substances that ionize in aqueous solution to produce $H^+_{(aq)}$ ions.
7. All acids are compounds of hydrogen.
8. A base is a substance that reacts with water to produce $OH^-_{(aq)}$ ions.

Part B: Written Response

Write your answers neatly and concisely. For full marks, your answers must show all pertinent explanations, calculations, and formulas.

9. Copy the following chart onto your answer sheet. What acid-base behaviour (acid, base, or neutral) would the following theories predict for the listed substances?

Substance	Lavoisier Theory	Davy/Liebig Theory	Arrhenius Theory	Revised Theory
HCl				
NH ₃				
KOH				
NaHCO ₃				
NO ₂				
CaO				

(9 marks)

10. State two limitations of the Arrhenius theory that led to its subsequent modification. (2 marks)
11. Use the revised or modified Arrhenius theory to answer this question.
- Write two equations to show how $\text{CO}_{2(g)}$ forms an acidic aqueous solution. (1 mark)
 - Write a balanced equation to show how $\text{HCN}_{(aq)}$ forms an acidic aqueous solution. (1 mark)
 - $\text{Li}_2\text{O}_{(s)}$ ionizes in water to form $\text{Li}^+_{(aq)}$ and $\text{O}^{2-}_{(aq)}$ ions. Write a balanced equation to show how $\text{O}^{2-}_{(aq)}$ could form a basic aqueous solution. (1 mark)
12. A scientist of the past said that science is built up with facts as a house is with stones, but a collection of facts is no more a science than a heap of stones is a house.

Write a short paragraph (1/3 to 1/2 page) explaining how this statement illustrates the nature of science. Use the development of the acid-base theory to illustrate your points. (3 marks)

Simplifying Things

– Brønsted-Lowry



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How do you eat an elephant? The straightforward answer is “One bite at a time!” Coming to a full understanding of the nature of acids and bases has been like trying to eat an elephant. Scientists have been chewing away at this elephant since the middle of the seventeenth century when the search for a comprehensive theory of acids and bases began in earnest. In Section 1, you studied those early theories, discovering that the meal of acid-base elephant was far from finished. Dessert was still a long way off!

In Section 2 you will examine a theory that comes close to what the original investigators began looking for – a theory that could both explain and predict acid-base behaviour. You will discover the details of this theory and then test its predictive power. You will see how, with a few small adjustments, its predictive power can be increased, but never made perfect. Finally, you will successfully use the acid-base theory to explain the behaviour of an amazing group of substances called indicators.

ACTIVITY

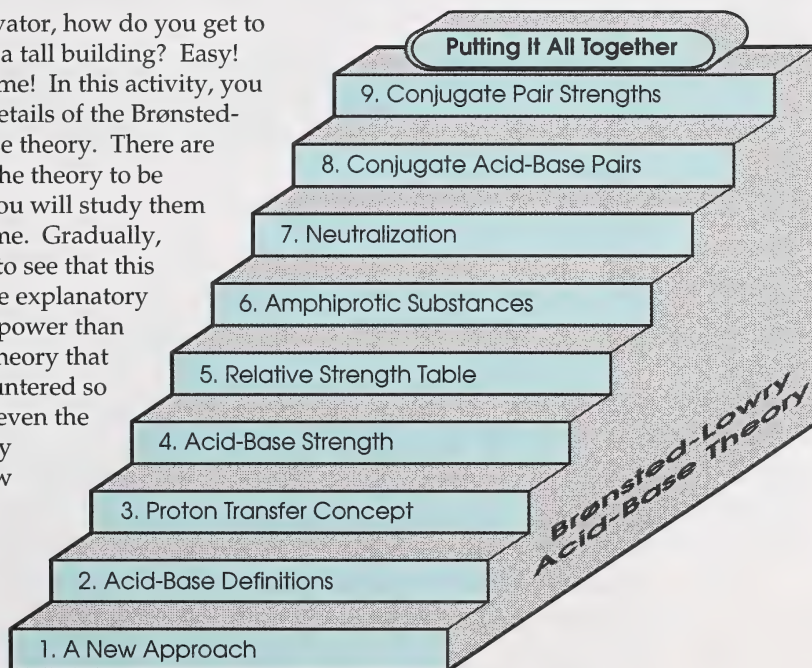
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Brønsted-Lowry Acids and Bases



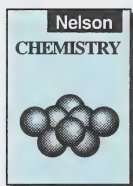
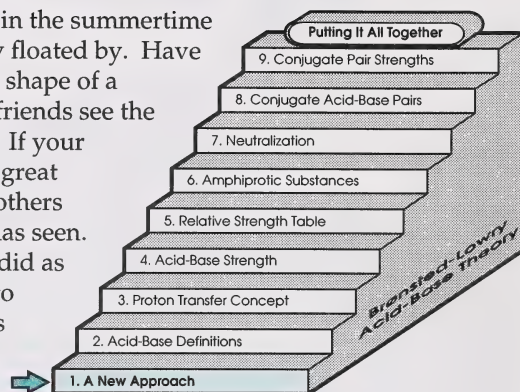
WESTFILE INC.

Without an elevator, how do you get to the top floor of a tall building? Easy! One step at a time! In this activity, you will learn the details of the Brønsted-Lowry acid-base theory. There are many parts of the theory to be examined, so you will study them one step at a time. Gradually, you will begin to see that this theory has more explanatory and predictive power than any acid-base theory that you have encountered so far. However, even the Brønsted-Lowry theory has a few shortcomings, which will be identified later in this section.



Step 1: A New Approach

You have probably lain back on the grass in the summertime and looked at the shapes of clouds as they floated by. Have you ever been the only one to identify the shape of a cloud as, say, an elephant, while all your friends see the shape of something completely different? If your answer is yes – good for you! Sometimes great progress is made when you look at what others have looked at and see what no one else has seen. This is exactly what Brønsted and Lowry did as they looked for a more successful theory to explain and predict the properties of acids and bases.



To learn more about the unique approach taken by Brønsted and Lowry in their search for a new definition of acids and bases, read pages 466 and 467 of your textbook.

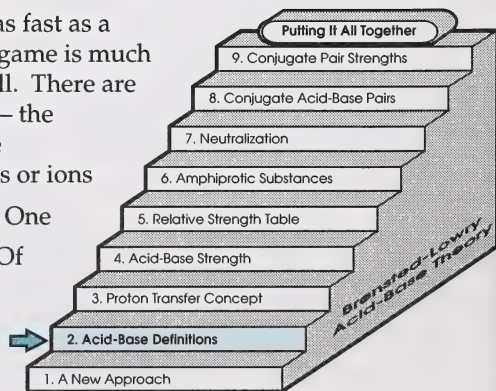
1. Contrast the approaches taken by early investigators with the approach taken by Brønsted and Lowry by completing the following:

Early investigators based their theories on _____ whereas Brønsted and Lowry focused on _____.

Check your answers by turning to the Appendix, Section 2: Activity 1.

Step 2: Acid-Base Definitions

Can you play catch by yourself? If you are as fast as a cartoon character, perhaps you can, but the game is much simpler if you have someone to catch the ball. There are two components necessary in playing catch – the thrower and the receiver. At first glance the Brønsted-Lowry theory is like two molecules or ions playing catch. The ball is a proton ($\text{H}^+(\text{aq})$). One molecule or ion throws; the other receives. Of course the proton is not really thrown! The proper term is *transferred*. A collision between an acid and a base results in a transfer of a proton from an acid to a base. In sports terms, it is more like a handoff.



Write the definitions of Brønsted-Lowry acids and bases by completing the following questions.

2. A Brønsted-Lowry acid is _____.

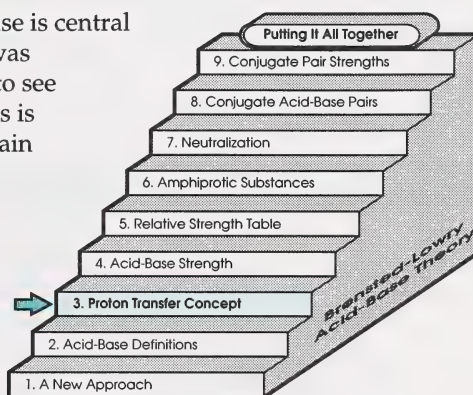
3. A Brønsted-Lowry base is _____.

Check your answers by turning to the Appendix, Section 2: Activity 1.

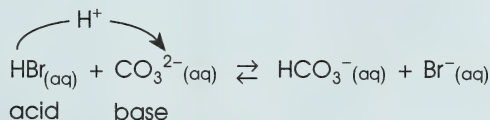
Did you notice that the Brønsted-Lowry definitions focus on what acids and bases do in a reaction, rather than on what the acid-base solutions do? This is quite a departure from past theories.

Step 3: Proton Transfer Concept – Revisited

The concept of proton transfer from acid to base is central to the Brønsted-Lowry theory. This concept was introduced in Section 1, Activity 2. Learning to see acid-base reactions as proton transfer reactions is extremely important, and will be reviewed again here.



Here is an example of the acid $\text{HBr}_{(\text{aq})}$ donating a proton to the base $\text{CO}_3^{2-}(\text{aq})$.

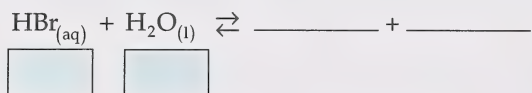


The $\text{CO}_3^{2-}(\text{aq})$ ion gains a positive charge as the H^+ joins it; $\text{CO}_3^{2-}(\text{aq})$ becomes $\text{HCO}_3^{-}(\text{aq})$. $\text{HBr}_{(\text{aq})}$ loses a positive charge as the H^+ leaves; $\text{HBr}_{(\text{aq})}$ becomes $\text{Br}^{-}(\text{aq})$.

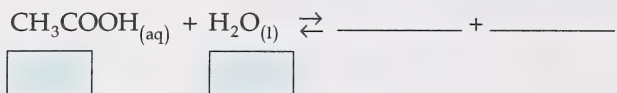
4. This question focuses on the concept of *proton transfer*. Complete the following for each statement.

- Draw an arrow to indicate the direction of proton transfer.
- Predict the products that will be formed with their correct charges.
- Classify each reactant as a Brønsted-Lowry *acid* or *base*.

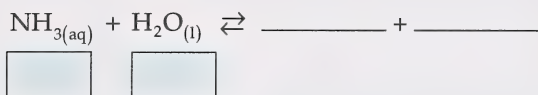
- a. the donation of a proton from $\text{HBr}_{(\text{aq})}$ to $\text{H}_2\text{O}_{(\text{l})}$



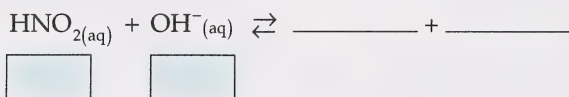
- b. the reaction between $\text{CH}_3\text{COOH}_{(\text{aq})}$ and $\text{H}_2\text{O}_{(\text{l})}$



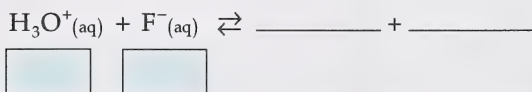
- c. the reaction between $\text{NH}_{3(\text{aq})}$ and $\text{H}_2\text{O}_{(\text{l})}$ to produce hydroxide ions



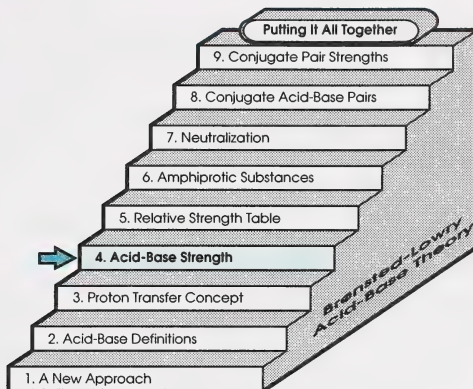
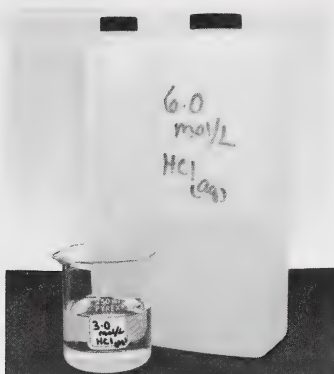
- d. the reaction between $\text{HNO}_{2(\text{aq})}$ and $\text{OH}^{-}(\text{aq})$



- e. the reaction between $\text{H}_3\text{O}^{+}(\text{aq})$ and $\text{F}^{-}(\text{aq})$



Check your answers by turning to the Appendix, Section 2: Activity 1.

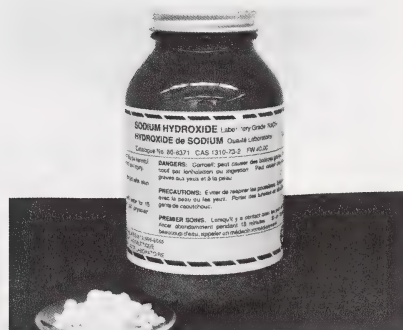
Step 4: The Concepts of Strong and Weak

A Brønsted-Lowry acid donates a proton to a base. The stronger the acid is, the better it is at releasing the proton to the receiving base. Those that react 100% (transfer *very close* to 100% of their protons to water) are called strong acids.

5. Complete the following chart.

Strong Acids	Weak Acids
• weak attraction for protons • donate protons readily	• •

A Brønsted-Lowry base accepts a proton from an acid. A strong base has a very strong attraction for protons, and a strong hold on the proton once accepted.

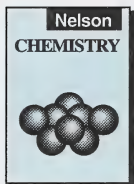
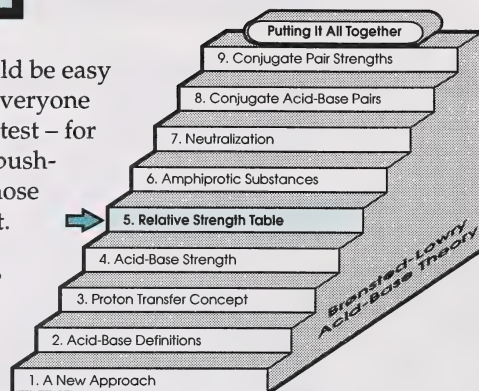


6. Complete the following chart.

Strong Bases	Weak Bases
• strong attraction for protons • accepts protons readily	• •

Step 5: The Relative Acid-Base Strength Table

How physically strong are Albertans? It would be easy to find out. All you would have to do is get everyone in the province to do exactly the same fitness test – for example, push-ups! Those who do the most push-ups would be considered the strongest and those who do the least could be considered weakest. Most would be in between. How could this principle be used to test the strength of acids? Of course you could not get them all to do push-ups! But you could get them all to do exactly the same test under identical conditions. You could compare the abilities of all acids to donate a proton to the same base – namely water. Those that donate protons most readily would be the strongest, and those that donate protons least readily would be the weakest. When you compare the abilities of a number of different substances to do the same thing, you can compare them to each other! It is that principle upon which the acid-base strengths table is built.



Turn to page 553 of *Nelson Chemistry* and use the Acids and Bases table to answer the following questions.

7. a. Create a table with the following headings:

Acid	Formula	Percent Reaction (%)	Equilibrium Constant (K_a)

In your table, list the relative strengths of the following 0.10 mol/L acids from strongest (first) to weakest (last). Include their percent reaction with water and their equilibrium constants.

- ammonium ion
 - hydrosulphuric acid
 - hydrogen carbonate ion
 - hydrogen borate ion
 - ethanoic acid
 - hydrogen sulphate ion
 - benzoic acid
 - hydroiodic acid
- b. What trend do you notice in the magnitude of percent reaction and equilibrium constants in the table? Explain the trends.

Check your answers by turning to the Appendix, Section 2: Activity 1.

Step 6: Amphiprotic Substances

In society, there are people who are *ambidextrous* – they can use both hands with equal ease. In nature, there is a class of animals which have characteristics of both fish and reptiles – amphibians (frogs, for example).

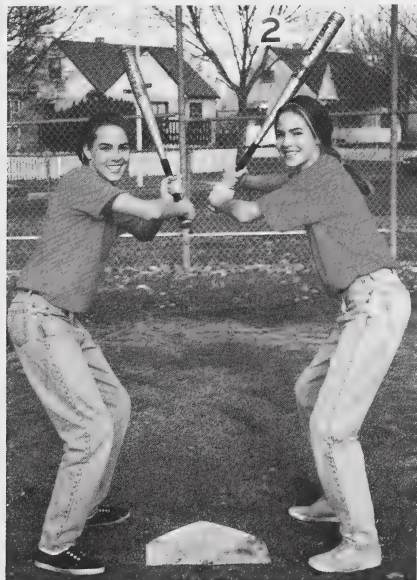
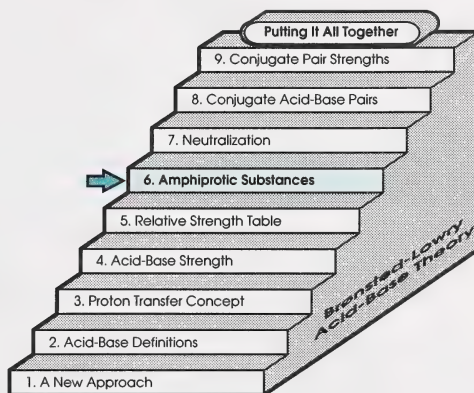
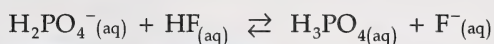
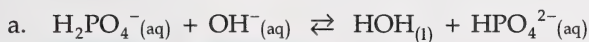


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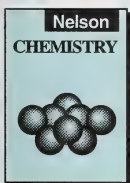


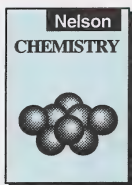
Even in baseball there are batters known as switch-hitters – they can bat from either side of the plate.

8. According to Brønsted-Lowry acid-base theory, some substances can act as an acid in some circumstances or as a base in other circumstances. These substances are called _____. (Review your reading on page 467 of *Nelson Chemistry*.)
9. Look carefully at the following two reactions. Identify each of the reactants in both reactions as a Brønsted-Lowry acid or base.



- b. The amphiprotic substance in part a. is _____.





10. a. Examine the Acids and Bases table on page 553 of *Nelson Chemistry*. Name the ten substances listed on the table that are amphoteric.
 b. What feature does each of the substances in your list have in common (except for water)?
11. Whether an amphoteric substance acts as an acid or a base is conditional. Re-examine the equations in question 9.a. Then use the acid-base strength table on page 553 of your textbook to see if you can synthesize a hypothesis to explain what those conditions for being the acid or base might be. Once you have an answer, complete the following sentences.
 a. An amphoteric substance will act as an acid if _____.
 b. An amphoteric substance will act as a base if _____.
12. Why does the Brønsted-Lowry theory still fall short of being a comprehensive theory of acids and bases?

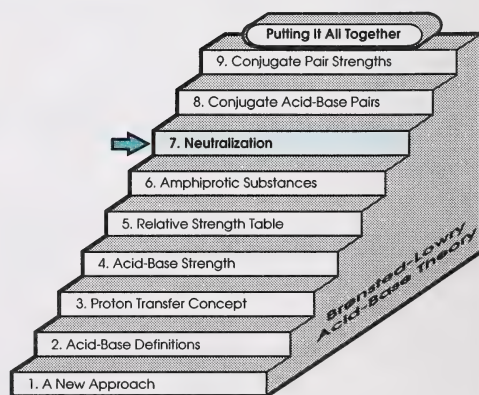
Check your answers by turning to the Appendix, Section 2: Activity 1.

You have seen that amphoteric substances show up on both sides of the Acids and Bases table. When identifying substances as possible acids or bases or both, it is important for you to remember to check **both** sides of the Acids and Bases table.

Step 7: Brønsted-Lowry Neutralizations

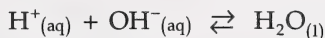
Have you ever stepped between two of your friends who were extremely angry with each other and calmed them down? If you succeeded, you neutralized a potentially harmful situation. Acids and bases can be very dangerous substances, yet when the two react with each other in the proper proportions, an amazing thing happens. Each one can **neutralize** the dangerous effects of the other. The resulting solution can be harmless.

neutralize – to eliminate the acidic or basic properties of the partner reactant

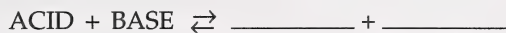


13. In a complete sentence, write the definition of a Brønsted-Lowry neutralization reaction.

14. You will recall that an Arrhenius neutralization is described by the equation



Complete the following word equation describing Brønsted-Lowry neutralizations.

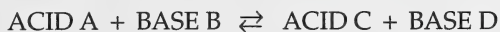


15. Do textbook questions 7, 8, and 9 on pages 467-468 of *Nelson Chemistry*.

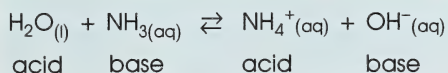
Check your answers by turning to the Appendix, Section 2: Activity 1.

Step 8: Conjugate Acid-Base Pairs

You have just seen that the products of a Brønsted-Lowry acid-base reaction are another acid and another base.



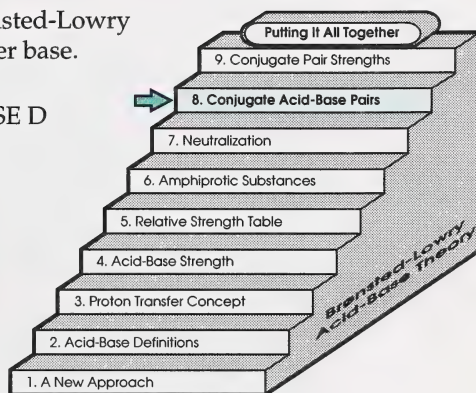
The following is an example of a real system:



The acid and base on the product side

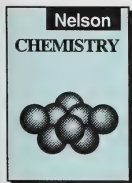
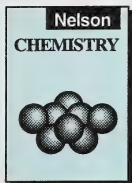
($\text{NH}_4^+_{(\text{aq})}$ and $\text{OH}^-_{(\text{aq})}$) can act as reactants

for the reverse reaction. Since there is both a forward and a reverse reaction possible in Brønsted-Lowry systems, they can be written as equilibrium systems.



There is an important relationship between the reactant acid ($\text{H}_2\text{O}_{(\text{l})}$) and the product base ($\text{OH}^-_{(\text{aq})}$) as well as between the reactant base ($\text{NH}_{3(\text{aq})}$) and the product acid ($\text{NH}_4^+_{(\text{aq})}$). To learn more about this relationship, read the first two paragraphs on page 468 in *Nelson Chemistry* and answer the following questions.

16. Define a conjugate acid-base pair.



17. Write the formulas of the conjugate bases of the following acids.

- | | | | |
|--|--|-------------------------------------|--|
| • $\text{HCl}_{(\text{aq})}$ | • $\text{HCO}_3^{-}(\text{aq})$ | • $\text{NH}_4^{+}(\text{aq})$ | • $\text{H}_2\text{CO}_{3(\text{aq})}$ |
| • $\text{H}_2\text{SO}_{4(\text{aq})}$ | • $\text{H}_2\text{PO}_4^{-}(\text{aq})$ | • $\text{H}_2\text{O}_{(\text{l})}$ | • $\text{HOOC}\text{COOH}_{(\text{aq})}$ |

18. Write the formulas for the conjugate acids of the following bases.

- | | | | |
|--------------------------------|---------------------------------|--------------------------------|---------------------------------|
| • $\text{Br}^{-}(\text{aq})$ | • $\text{PO}_4^{3-}(\text{aq})$ | • $\text{HO}_2^{-}(\text{aq})$ | • $\text{HCO}_3^{-}(\text{aq})$ |
| • $\text{NO}_2^{-}(\text{aq})$ | • $\text{HSO}_4^{-}(\text{aq})$ | • $\text{HS}^{-}(\text{aq})$ | • $\text{CO}_3^{2-}(\text{aq})$ |

Check your answers by turning to the Appendix, Section 2: Activity 1.

The components of a Brønsted-Lowry system, that you have studied so far, fit together as follows:

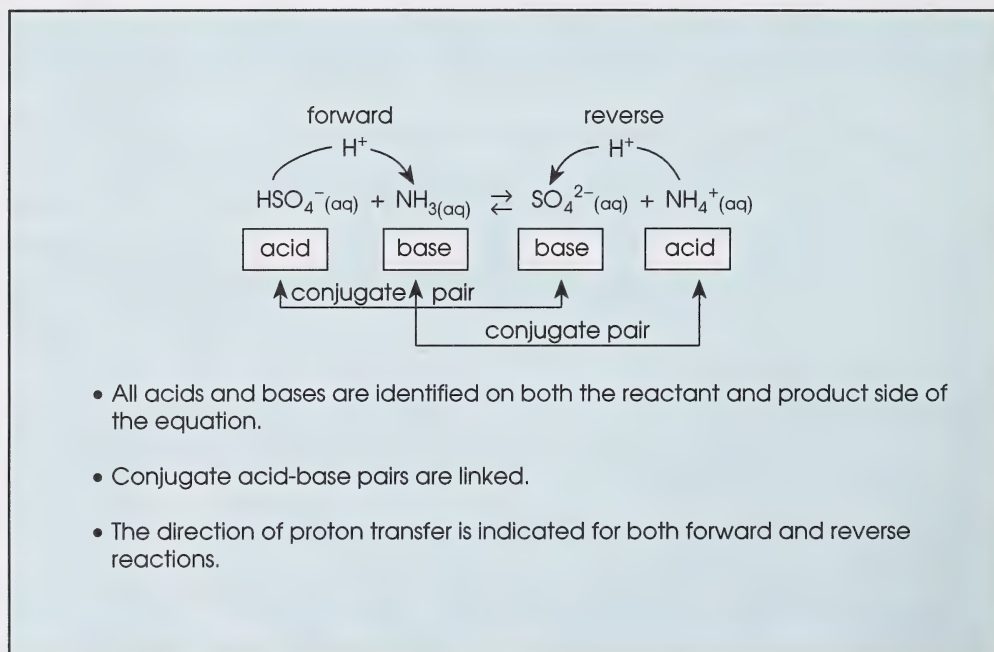


FIGURE 6.1: Components of a Brønsted-Lowry System

You can see from Figure 6.1 that an acid, having donated its proton, becomes a base (a conjugate pair), and that a base, having accepted a proton, becomes an acid (a conjugate pair). The following questions will help you develop your understanding of all the interrelated components of a Brønsted-Lowry acid-base system.

19. Indicate the following for each given reaction:

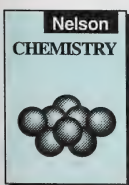
- Predict the products where required.
- Identify the acids and bases on both the reactant side and the product side of the equation.
- Draw an arrow to indicate the direction of proton shift for both the reactant side and the product side.
- Connect the acid-base conjugate pairs.

Note: You may use Figure 6.1: Components of a Brønsted-Lowry System as a guide to answering this question.

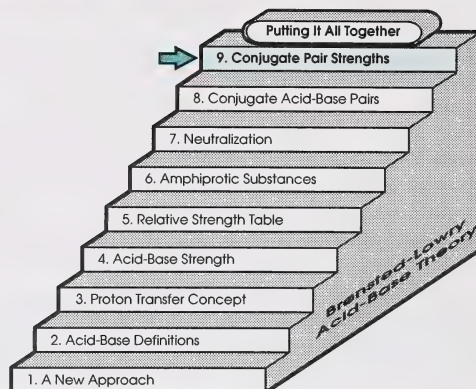
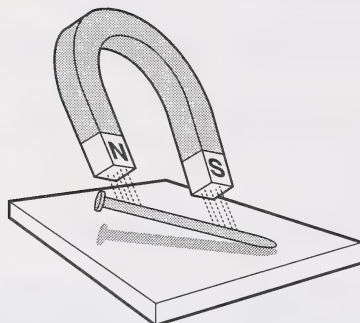
- $\text{H}_2\text{S}_{(\text{aq})} + \text{NH}_{3(\text{aq})} \rightleftharpoons \text{HS}^{-}_{(\text{aq})} + \text{NH}_4^{+}_{(\text{aq})}$
- $\text{H}_2\text{SO}_{4(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{_____} + \text{_____}$
- $\text{H}_2\text{O}_{(\text{l})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{_____} + \text{_____}$
- $\text{H}_2\text{PO}_4^{-}_{(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{H}_3\text{PO}_{4(\text{aq})} + \text{OH}^{-}_{(\text{aq})}$
- $\text{H}_2\text{PO}_4^{-}_{(\text{aq})} + \text{H}_2\text{PO}_4^{-}_{(\text{aq})} \rightleftharpoons \text{H}_3\text{PO}_{4(\text{aq})} + \text{HPO}_4^{2-}_{(\text{aq})}$
- $\text{Fe}(\text{H}_2\text{O})_6^{3+}_{(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{Fe}(\text{H}_2\text{O})_5(\text{OH})^{2+}_{(\text{aq})} + \text{H}_3\text{O}^{+}_{(\text{aq})}$
- $\text{H}_2\text{SO}_{3(\text{aq})} + \text{HS}^{-}_{(\text{aq})} \rightleftharpoons \text{HSO}_3^{-}_{(\text{aq})} + \text{H}_2\text{S}_{(\text{aq})}$
- $\text{HPO}_4^{2-}_{(\text{aq})} + \text{HCO}_3^{-}_{(\text{aq})} \rightleftharpoons \text{H}_2\text{PO}_4^{-}_{(\text{aq})} + \text{CO}_3^{2-}_{(\text{aq})}$
- $\text{CH}_3\text{COOH}_{(\text{aq})} + \text{SO}_4^{2-}_{(\text{aq})} \rightleftharpoons \text{_____} + \text{_____}$

20. Do textbook questions 11 and 12 on page 470 of *Nelson Chemistry*.

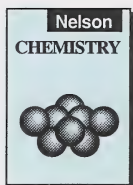
Check your answers by turning to the Appendix, Section 2: Activity 1.



Step 9: Relative Conjugate Pair Strengths



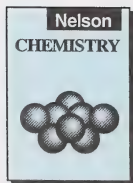
If a powerful magnet strongly attracts an iron nail, can the magnet *change its mind* and suddenly decide to be weakly attracted to the nail – or perhaps repel it completely? Can a weak magnet have a powerful attraction for a nail? Of course not! Magnets attract iron either strongly or poorly, but they cannot do both at the same time.



You have just discovered that an acid becomes a conjugate base with the transfer of a proton. Can a strong acid, which donates a proton easily, produce a conjugate base that accepts protons strongly? Answer this question by reading page 469 (starting from the given equation) in your textbook.

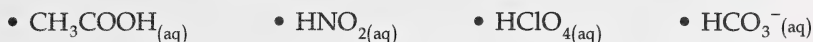
21. Reproduce the following chart and fill in the missing information.

Acid		Conjugate Base	
_____ Acid	gives rise to	_____ Conjugate Base	
↓ decreasing strength of acid		↑ decreasing strength of base	
_____ Acid	gives rise to	_____ Conjugate Base	



Notice how similar the chart in the preceding question is to the structure of the relative acid-base strength table (titled Acids and Bases) on page 553 of *Nelson Chemistry*.

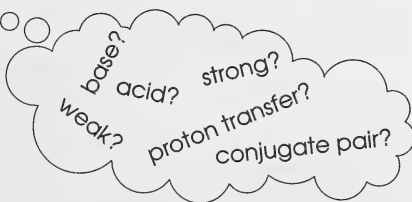
22. Using the Acids and Bases table on page 553 of *Nelson Chemistry*, list the following acids in decreasing order of strength.



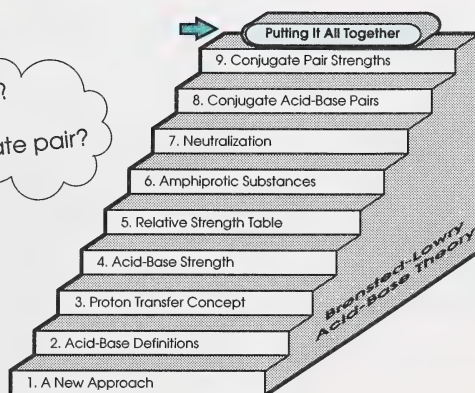
23. List the conjugate bases of the acids given in the preceding question in decreasing order of strength.

Check your answers by turning to the Appendix, Section 2: Activity 1.

Putting It All Together

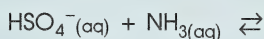


All the parts of the Brønsted-Lowry theory will now be tied together as you analyse a Brønsted-Lowry system. Consider the following Brønsted-Lowry system:



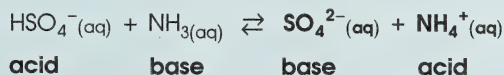
Example:

Analyse the following system:

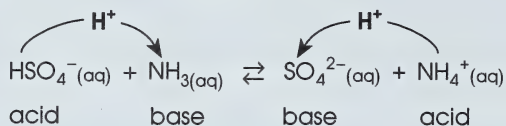


The complete analysis of this system involves the following steps:

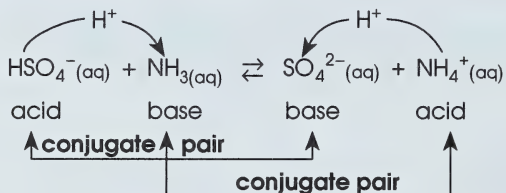
- a. If the products are not provided, predict their formulas and charges. Label all species present in the equilibrium system as to whether they serve as an acid or a base.



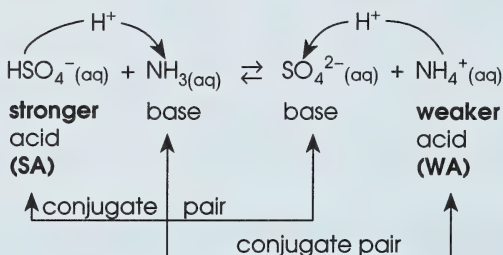
- b. Draw arrows indicating the direction of the proton transfer for both the forward and reverse reactions.



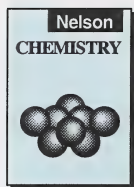
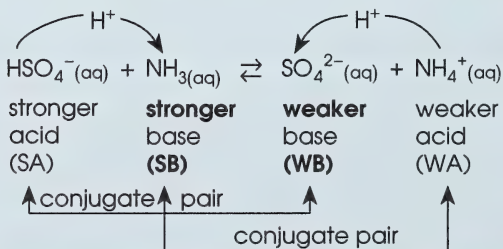
- c. Link and label the respective conjugate acid-base pairs.



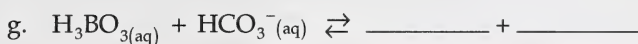
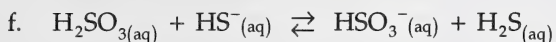
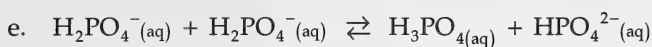
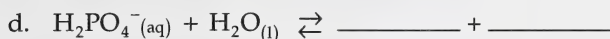
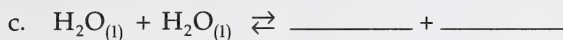
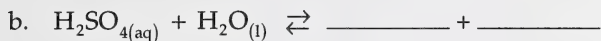
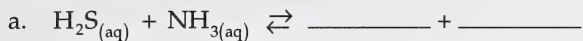
- d. Use the Acids and Bases table on page 553 of *Nelson Chemistry* to determine which of the two competing acids is the stronger.



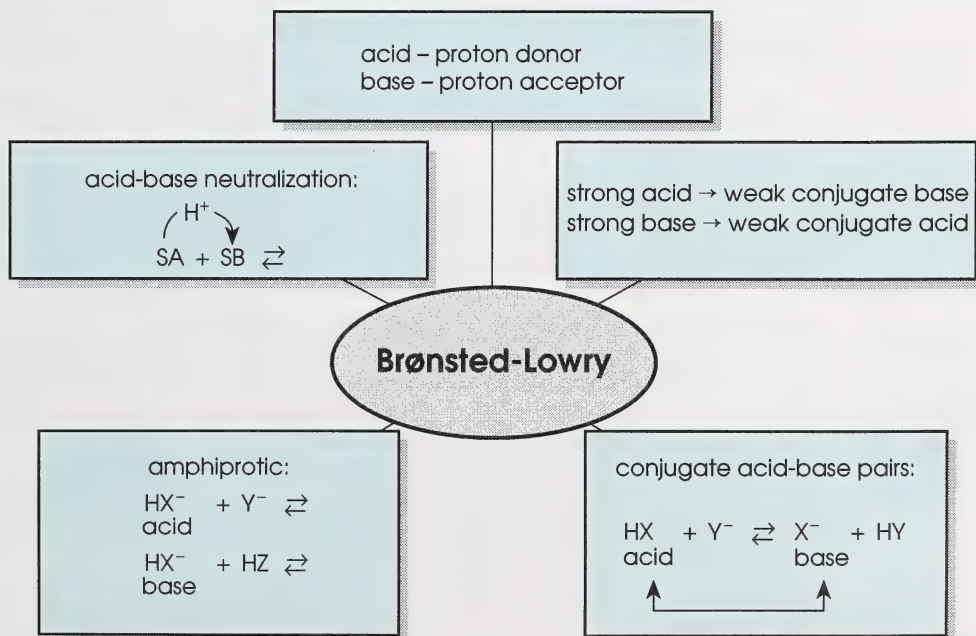
- e. Using your knowledge that a stronger acid gives rise to a weaker conjugate base and that a weaker acid gives rise to a stronger conjugate base, complete the labelling of the other substances in the system.



24. Analyse the following Brønsted-Lowry systems. You can use the abbreviations (for example, stronger acid – SA) as shown in the preceding example to label the participants.



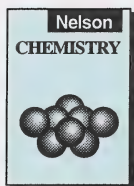
Check your answers by turning to the Appendix, Section 2: Activity 1.



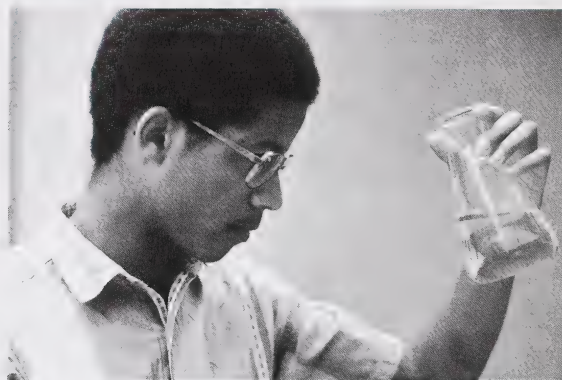
In this activity, you took a step-by-step approach to learning the many interrelated pairs of the Brønsted-Lowry theory of acids and bases. You have discovered how to completely analyse a Brønsted-Lowry equilibrium system. In the following activities, you will test the predictive power of the theory.

ACTIVITY

2 Which Way Will It Shift?

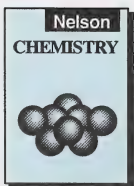


In Activity 1, you learned that for all its advantages, the Brønsted-Lowry theory still cannot predict certain features of acids and bases. It cannot predict whether an acid on its own will be strong or weak and therefore it cannot predict whether an acid-base system will favour reactants or products at equilibrium. Read the paragraph Predicting Acid-Base Equilibria on page 473 of *Nelson Chemistry* to learn what alternative approach there might be that will enable you to make accurate predictions.



1. When a theory is unable to predict, what strategy is employed as a substitute for theoretical predictions?

Check your answers by turning to the Appendix, Section 2: Activity 2.



In Module 3 of this course you used an empirical generalization while learning how to predict whether or not redox reactions would be spontaneous. Recall that the relative position of the oxidizing agent (OA) and reducing agent (RA) on the Redox Half-Reactions table (page 552 of *Nelson Chemistry*) could be used to determine whether or not a reaction was spontaneous. In equilibrium terminology, that is the same as predicting whether reactants or products are favoured at equilibrium. Since the redox table and the Acids and Bases table (page 553 of *Nelson Chemistry*) are so alike in structure, could a similar generalization, based on relative position on the table, make it possible to predict the equilibrium behaviour of acids and bases?

2. Complete the following chart to review the design of both the Redox Half-Reactions table and the Acids and Bases table.

Redox Half-Reactions Table		Acids and Bases Table	
stronger OA	gives rise to	_____	gives rise to
↓ decreasing OA strength		↓ []	
weaker OA	gives rise to	_____	gives rise to
		↑ []	
		stronger RA	

Check your answers by turning to the Appendix, Section 2: Activity 2.

Will you be able to predict the extent of an equilibrium based on the relative positions of the reactant acids and bases? To find out, do the following lab exercise.

Lab Exercise 15C: Position of Acid-Base Equilibria

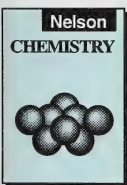
Carefully read and do Lab Exercise 15C: Position of Acid-Base Equilibria on pages 473-474 of *Nelson Chemistry*. Pay special attention to the applied science skills.

3. Summarize your results from the lab exercise in a table similar to the following:

Reaction Number	Percent Reaction (%)	Equilibrium Favours (reactants or products)	Relative Position of Reactants on Table of Acids and Bases
1	<50		
2	>99		
3	<50		
4	>50		
5	<50		
6	>99*		

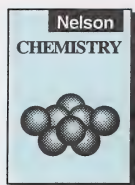
* Recall that a single reaction arrow (→) implies a quantitative (>99%) reaction.

4. As your analysis, write a generalization that describes how the positions of the reactant acid and base in the acid-base table relate to the position of the equilibrium of each reaction system.



Science Skills

- ☐ A. Initiating
- ☐ B. Collecting
- ☐ C. Organizing
- ☒ D. Analysing
- ☐ E. Synthesizing
- ☒ F. Evaluating



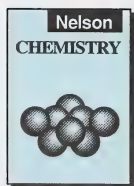
5. Based on your generalization and the acid-base table on page 553 of your textbook, indicate whether the following systems will favour reactants or products at equilibrium.
- Acetic (ethanoic) acid reacts with the hydrogen sulphide ion.
 - Hypochlorous acid reacts with the nitrite ion.
 - Nitrous acid reacts with the sulphate ion.
 - Hydrochloric acid reacts with the hydroxide ion.
 - Methanoic acid reacts with the carbonate ion.

Check your answers by turning to the Appendix, Section 2: Activity 2.

Acid Above Base – Favours Products



Acid Below Base – Favours Reactants



Making complex predictions often requires a synthesis of a number of ideas. To learn the details of a process that allows you to make accurate predictions about all the events in Brønsted-Lowry systems, read pages 474-475 in *Nelson Chemistry*. Then answer the following questions.



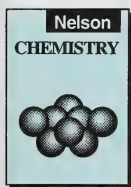
- What two ideas are brought together that enable you to predict the products and the extent of reaction of a Brønsted-Lowry system?
- Because an acid-base system is a competition for protons, it is most probable that the _____ (strongest/weakest) acid will donate protons to the _____ (strongest/weakest) base.

8. a. Fill in the missing parts of a table similar to the following:

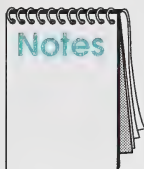
PREDOMINANT SPECIES IN AQUEOUS SOLUTION	
Substance Dissolved	Predominant Species (Atoms, Ions, or Molecules)
	separate ions
strong acid	
	molecules

- b. In Module 3, you predicted the oxidizing and reducing agents and used a five-step method of predicting reactions. How does the redox method of listing the predominant species in aqueous solution compare to the acid-base method of listing species? (Remember, *compare* means similarities **and** differences.)

Check your answers by turning to the Appendix, Section 2: Activity 2.



A very useful method that allows you to predict the reactants and products in a reaction as well as the position at equilibrium, is known as the five-step method of analysis. Study the example of how to use the five-step method on the bottom of page 475 of *Nelson Chemistry*. Then review the summary information on pages 475-476.

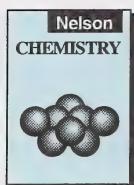


Important points about the example on page 475 of your textbook

- Strong acids are listed as $\text{H}_3\text{O}^+_{(\text{aq})}$ plus the conjugate base, not as $\text{H}^+_{(\text{aq})}$ plus the conjugate base.
- The single arrow in the example equation implies >99% reaction (quantitative). You are not expected to predict this (your textbook just put it in to be more descriptive); you are only expected to predict *favours products* (>50%) or *favours reactants* (<50%).

9. Use the five-step method for predicting these acid-base reactions.

- a. A reaction occurs when methanoic acid ($\text{HCOOH}_{(\text{aq})}$) is mixed with a sodium nitrite solution ($\text{NaNO}_{2(\text{aq})}$).
- b. Vigorous bubbling occurs when a strong acid ($\text{HCl}_{(\text{aq})}$) reacts with a sodium bicarbonate solution ($\text{NaHCO}_{3(\text{aq})}$).



10. Do textbook questions 16-23 on page 476 of *Nelson Chemistry*.

Check your answers by turning to the Appendix, Section 2: Activity 2.

You have examined and worked with a method of making complex predictions about Brønsted-Lowry acid-base systems. Does the five-step method always work? You will find out in Activity 3.

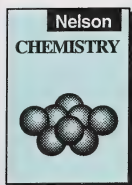
ACTIVITY

3 Testing the Predictions



ALBERTA ENVIRONMENT SERVICE

People make predictions all the time. You might predict the weather (like the meteorologist shown in the photograph) or the score of a football or hockey game. You have probably predicted your mark on an exam or test. How do you test the accuracy of your predictions? Usually it is time that tells you whether or not your predictions are accurate. In science, time is not a sufficient test. The accuracy of predictions must be tested rigorously in the laboratory using methods of scientific investigation. In this activity, you will test the reliability of the five-step method and the ability of the Brønsted-Lowry concept to predict acid-base behaviour.



How reliable is the five-step method at predicting the products and extent of reaction for acid-base systems? To find out, do Lab Exercise 15D on pages 476–477 of *Nelson Chemistry*. Pay special attention to the applied science skills.

Lab Exercise 15D: Testing the Five-Step Method

Guidelines

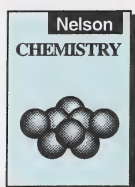
- Omit the reaction in this exercise that uses baking soda and lye ($\text{NaOH}_{(\text{aq})}$).
- Consider the $\text{HCl}_{(\text{aq})}$ reaction as Reaction 1, the $\text{CH}_3\text{COOH}_{(\text{aq})}$ reaction as Reaction 2, and the $\text{NH}_{3(\text{aq})}$ reaction as Reaction 3.

1. Predict the reactants, products, and extent of the equilibrium for each reaction.
2. The following questions will help you analyse the data given in the evidence table on page 477 of your textbook to determine the actual products and extent of reaction. Assume that bubbles are produced in Reactions 1 and 2 as a result of the further decomposition of $\text{H}_2\text{CO}_{3(\text{aq})}$ in the reaction $\text{H}_2\text{CO}_{3(\text{aq})} \rightleftharpoons \text{H}_2\text{O}_{(\text{l})} + \text{CO}_{2(\text{g})}$.
 - a. Does the evidence from Reaction 1 support your prediction of the products of the reaction? Explain.
 - b. What evidence from Reaction 1 can be used to support your prediction of the extent of reaction? Explain.
 - c. Does the evidence from Reaction 2 support your prediction of the products of the reaction? Explain.
 - d. What evidence from Reaction 2 can be used to support your prediction of the extent of reaction? Explain.
 - e. Does any evidence from Reaction 3 support your prediction of the products of the reaction? Explain.
 - f. What evidence from Reaction 3 can be used to support your prediction of the extent of reaction? Explain.
3. Based on your data and analysis information, what conclusion can you draw about the ability of the five-step method to predict the products and extent of reaction for a Brønsted-Lowry acid-base system?

Check your answers by turning to the Appendix, Section 2: Activity 3.

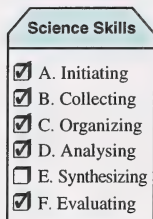
With some confidence in the five-step method, you can now test the Brønsted-Lowry concept of acids and bases at some length.

Investigation 15.2: Testing Brønsted-Lowry Predictions



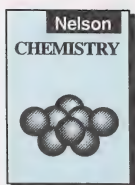
Perform Investigation 15.2 as described on page 477 of *Nelson Chemistry*. Carefully follow the directions given for this investigation. Pay special attention to the required components, safety aspects, and applied science skills.

Guidelines



- If you are not using supervised laboratory facilities, you will not be doing Reaction 8 (sodium hydrogen sulphate in water). The predicted reaction is still expected, though.
 - Use a volume equivalent to about one-third of a small test tube for each solution.
 - All solutions in this investigation may be poured down the sink, followed by a good rinse of water. Solid waste should go into a solid waste container.
4. Use the five-step method to predict the products and extent of the reaction equilibrium for each of the reactions in the investigation. Construct a table in which to organize your predicted reactions and observations.
 5. Write a procedure that will enable you to employ certain diagnostic tests to determine the actual products and extent of reaction for each of the reactions in the investigation.
 6. Construct a data table in which to organize the results of your diagnostic tests. Carry out your procedure. Carefully record your observations.
 7. Were there any reactions for which the evidence clearly disagreed with the prediction? If so, which one(s)?
 8. Evaluate your results. What conclusion can you draw about the ability of the Brønsted-Lowry theory to predict products and extent of reaction using the five-step method of empirical generalization?

Check your answers by turning to the Appendix, Section 2: Activity 3.



Can the empirical generalization developed in Lab Exercise 15C be combined with the Brønsted-Lowry acid-base theory to predict the relative strengths of acids? To find out, do Lab Exercise 15E on pages 477-478 of *Nelson Chemistry*. Pay special attention to the applied science skill.

Lab Exercise 15E: An Acid-Base Table

Science Skills

- ☐ A. Initiating
☐ B. Collecting
☐ C. Organizing
☒ D. Analysing
☐ E. Synthesizing
☐ F. Evaluating

9. Analyse the evidence provided on page 478 of *Nelson Chemistry* to determine the relative strengths of the acids. Record your analysis in a table similar to the following.

Acid		Conjugate Base	
SA ↓ WA			↑

Check your answers by turning to the Appendix, Section 2: Activity 3.

In this activity you have discovered that the Brønsted-Lowry theory by itself still has a somewhat limited ability to predict acid-base behaviour and the extent of a reaction equilibrium. The combination of the Brønsted-Lowry theory with certain empirical generalizations greatly increases its predictive powers. Nevertheless, the Brønsted-Lowry theory will still have to be revised.

(Optional) Read the brief description of the next stage in acid-based theory, the Lewis acid-base theory, on the bottom of page 478 of *Nelson Chemistry*.

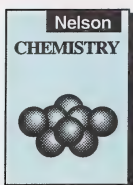
ACTIVITY

4

The Magic of Indicators

One rarely has the opportunity to meet a molecule that talks to you. Acid-base indicators can talk to you, but not in English. They use sign language! Using sign language, they tell you what they are doing and when they are doing it. Their message is unmistakable – sudden and dramatic! In this activity you will learn the language of acid-base indicators. Specifically, you will review what they are and what they do (their empirical definitions were introduced in Chemistry 20), and you will discover why they work the way they do (their theoretical definition). The Brønsted-Lowry theory will form the basis of your understanding. What looks like magic will become perfectly understandable in the light of a working theory.

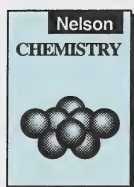




To review what indicators do, read the first paragraph on page 470 of *Nelson Chemistry* and answer the following questions.

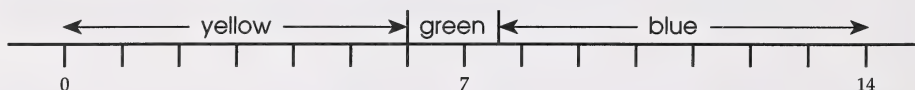
- Complete the following sentence: Acid-base indicators are substances that _____.
- What are two of the most common indicators used in the science lab, and what are their two colours?

Indicator	Colour 1	Colour 2

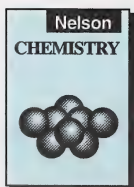


There are many indicators besides the two mentioned in the preceding question, some of which have more complicated colour changes. On the inside of the back cover of *Nelson Chemistry* is a table of acid-base indicators. Turn to the table at this time and find the indicator called bromothymol blue.

The following scale illustrates the colour changes that bromothymol blue exhibits throughout the range of the pH scale.



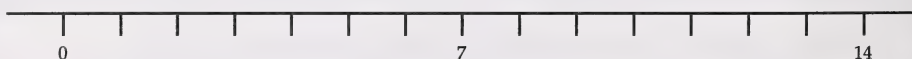
Notice that as the colour of the indicator changes from yellow to blue, it passes through an intermediate colour – green. This intermediate colour occurs in what is known as the colour change range for that indicator. This colour change is more clearly illustrated on the Acid-Base Indicators Colour Chart located in the Chemistry Data Booklet in the Module 7 Appendix.



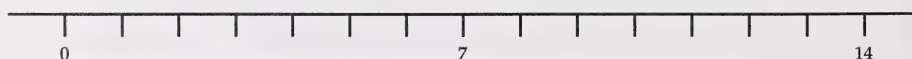
Use the Acid-Base Indicators table (inside back cover of *Nelson Chemistry*) to answer the following questions.

- Indicate the colour changes and associated pH values on the pH scales for the following indicators. Predict the intermediate colour that occurs in the colour change range.

a. alizarin yellow R



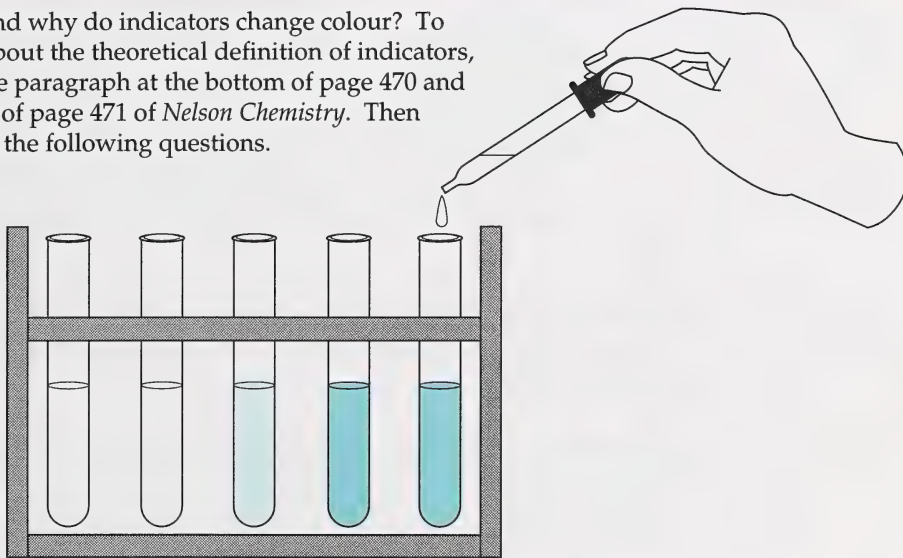
b. methyl orange



4. What would be the predominant colour in the colour change range of the indicator indigo carmine?
5. What is the colour of the indicator thymolphthalein in a solution with a pH of 12.8?
6. What is the colour of the indicator chlorophenol red in a solution with $[H^+_{(aq)}] = 1.58 \times 10^{-6} \text{ mol/L}$?
7. Do textbook questions 13 and 14 on page 472 of *Nelson Chemistry*.

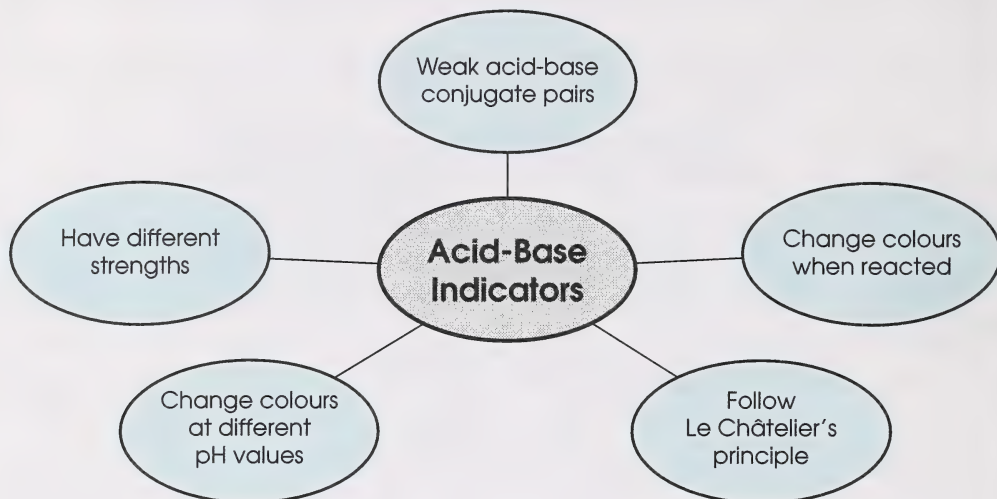
Check your answers by turning to the Appendix, Section 2: Activity 4.

How and why do indicators change colour? To learn about the theoretical definition of indicators, read the paragraph at the bottom of page 470 and the top of page 471 of *Nelson Chemistry*. Then answer the following questions.



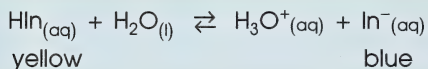
8. Complete the following sentence: An indicator is a _____.
9. Using the generalized reaction at the top of page 471 of your textbook as an example, write Brønsted-Lowry equations to show how the following indicators will react with water to form their conjugate bases. Link the conjugate pairs and indicate their respective colours. Use the Acid-Base Indicators table (back inside cover of *Nelson Chemistry*) where necessary. The symbols for the indicators are given in parenthesis.
 - a. bromothymol blue (HBb)
 - b. methyl orange (HMo)
 - c. methyl red (HMr)
 - d. thymol blue (H_2Tb)

10. (True or False) If an acid $\text{HX}_{(\text{aq})}$ is to be useful as an indicator, the molecule $\text{HX}_{(\text{aq})}$ should be the same colour as the ion $\text{X}^{-}(\text{aq})$.

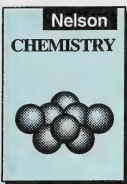


What causes the indicator equilibrium to shift right or left, causing the indicator to change colour?

11. Use the given reaction for the hypothetical indicator $\text{HIn}_{(\text{aq})}$ to answer the following questions. Use Le Châtelier's principle to predict the direction of the equilibrium shift.



- If a strong acid were added to the equilibrium system, which direction would the equilibrium shift?
- What colour would the indicator be in a solution with a high hydronium ion concentration (strong acid)?
- If a basic solution were gradually added to this system, the added $\text{OH}^{-}_{(\text{aq})}$ ions would react with the $\text{H}_3\text{O}^{+}_{(\text{aq})}$ ions. Write the equation describing this reaction.
- If $\text{H}_3\text{O}^{+}_{(\text{aq})}$ were gradually removed by the addition of $\text{OH}^{-}_{(\text{aq})}$, which direction would the $\text{HIn} - \text{In}^{-}$ equilibrium shift? What colour would the solution become?



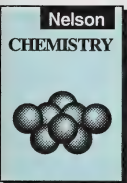
12. Do textbook question 15 on page 472 of *Nelson Chemistry*.

Check your answers by turning to the Appendix, Section 2: Activity 4.

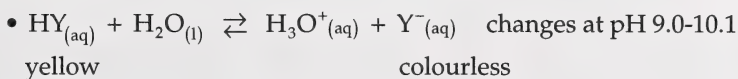
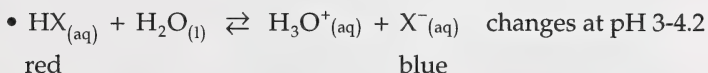
As you examine the indicator table, it is evident that different indicators change colours at different pH values. Why do some indicators change colour at lower pH values while others do so at higher pH values?

13. Fill in the blanks in the following paragraph.

Indicators (HIn) that change colour at low pH values do so because they are stronger acids. As stronger acids they have _____ (weaker/stronger) H – In bonds. They donate their protons _____ (easily/poorly) to the added base since they can compete effectively with the hydronium ion to donate protons. This occurs at _____ (lower/higher) pH values. Indicators whose colour change range occurs at higher pH values are _____ (weaker/stronger) acids with _____ (weaker/stronger) H – In bonds. The proton donation and subsequent colour change take place at higher $\text{OH}^-_{(\text{aq})}$ concentrations and therefore at higher pH values.



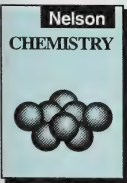
14. Three indicators are listed among the acids on the Acids and Bases table on page 553 of *Nelson Chemistry*. List them from strongest to weakest. Compare their order of appearance to their order of appearance on the indicator chart on the back inside cover. What conclusion can you draw from this observation?
15. What can you conclude about the acid strengths of indicators $\text{HX}_{(\text{aq})}$ and $\text{HY}_{(\text{aq})}$ from the following information?

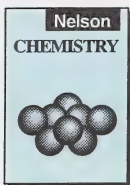


Read the section titled pH Test Strips on page 471 and the top of page 472 (margin) of *Nelson Chemistry* to learn about some applications of acid-base indicators in society.

16. Briefly describe one commercial (or household) use or application for pH test strips.

Check your answers by turning to the Appendix, Section 2: Activity 4.





From previous textbook questions 13-15 on page 472 of *Nelson Chemistry*, you have seen that indicators are often used to estimate the pH of unknown solutions. As a further example of this, do Lab Exercise 15A on pages 472-473 of *Nelson Chemistry*. Pay special attention to the applied science skill.

Lab Exercise 15A: Using Indicators to Determine pH

Science Skills

- ☐ A. Initiating
- ☐ B. Collecting
- ☐ C. Organizing
- ☒ D. Analysing
- ☐ E. Synthesizing
- ☐ F. Evaluating

17. Summarize the evidence on a chart similar to the following.

Indicator	Solution A Colours	Indicator	Solution B Colours	Indicator	Solution C Colours
methyl violet		indigo carmine		phenolphthalein	
methyl orange		phenol red		thymol blue	
methyl red		bromocresol green		bromocresol green	
phenolphthalein		methyl red		methyl orange	

18. Analyse the data and determine the pH of the three solutions. You may wish to use a table to organize your analysis.
19. A student who wanted to determine the pH of an unknown solution recorded these observations:

Indicator	Colour of the Indicator in the Solution
methyl orange	yellow
methyl red	yellow
bromothymol blue	blue
phenolphthalein	colourless

What is the most likely pH of the solution to the nearest whole number?

Check your answers by turning to the Appendix, Section 2: Activity 4.

Acid-base indicators are very useful tools. They can help you estimate the pH of a solution or highlight the endpoint of a titration. There is no magic involved, although it may look like it; it is just good chemistry.

Follow-up Activities

If you had difficulties understanding the concepts in the activities, it is recommended that you do the Extra Help. If you have a clear understanding of the concepts, it is recommended that you do the Enrichment.

Extra Help

There were three main ideas developed in this section.

- You began this section by learning the many components of the Brønsted-Lowry theory of acids and bases. This theory marks the end (in this course) of the parade of theories that began in Section 1.
- By itself, the Brønsted-Lowry theory was not able to predict the products for all acid-base reactions, nor was it able to predict the extent of reaction equilibrium for some acid-base reactions.

An empirical generalization that paralleled the one developed for oxidation-reduction reactions (acid above base – favours products; acid below base – favours reactants) and a five-step method for predicting the products of an acid-base reaction was developed and used to enhance the Brønsted-Lowry theory's predictive power.

- Finally, although the Brønsted-Lowry theory was not completely successful, it was used to explain and predict the behaviour of acid-base indicators.

Answering the following questions will help you review these ideas.

1. The major concepts of the Brønsted-Lowry theory can be reviewed by answering the questions in the following concept flow chart. Use only key words or phrases to summarize the seven points.

Brønsted-Lowry Review

I. Definitions	
Acid –	example _____
Base –	example _____

Brønsted-Lowry Review – cont'd

II. Proton Transfer

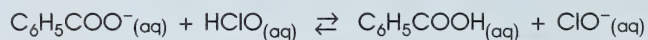
- a. Protons transfer from _____ to _____.
- b. Write the equation for the reaction between $\text{HCN}_{(\text{aq})}$ and $\text{NaCH}_3\text{COO}_{(\text{aq})}$.
Show the direction of proton transfer and predict the products.
- _____
- c. Write the equation for the reaction between $\text{NaH}_2\text{PO}_{4(\text{aq})}$ and $\text{HSO}_4^{-}(\text{aq})$.
Show the direction of proton transfer and predict the products.
- _____

III. Concept of Weak and Strong

Strong acid –	example _____
Weak acid –	example _____
Strong base –	example _____
Weak base –	example _____

IV. Predicting Extent of Reaction

- a. The equilibrium generalization says that if the reactant acid is _____ (higher/lower) than the reactant base on the Acids and Bases table, equilibrium will favour products. If the reactant acid is lower than the reactant base, equilibrium will favour _____.
- b. Will the following equilibrium system favour reactants or products?



Brønsted-Lowry Review – cont'd**V. Neutralization**

- a. Complete the following word equation: $\text{ACID} + \text{BASE} \rightleftharpoons \text{_____} + \text{_____}$
- b. Identify the acid and the base on both sides of the following equations. Indicate the direction of the proton transfer.
- $\text{H}_3\text{PO}_{4(\text{aq})} + \text{CN}^-_{(\text{aq})} \rightleftharpoons \text{HCN}_{(\text{aq})} + \text{H}_2\text{PO}_4^-_{(\text{aq})}$
 - $\text{C}_6\text{H}_5\text{COO}^-_{(\text{aq})} + \text{HClO}_{(\text{aq})} \rightleftharpoons \text{C}_6\text{H}_5\text{COOH}_{(\text{aq})} + \text{ClO}^-_{(\text{aq})}$

VI. Conjugate Pairs – What Are They?

In any conjugate pair, one member of the pair is an _____ and the other member of the pair is a _____. They differ by only one _____. An acid on the reactant side becomes a _____ on the product side. A base on the reactant side becomes a(n) _____ on the product side. If an acid is strong, its conjugate base is _____. If an acid is weak, its conjugate base is _____.

VII. Putting It All Together

Complete analysis of a system requires

- Predicting products (if required)
- Showing proton transfer
- Identifying all acids and bases
- Connecting conjugate pairs
- Identifying which member of each pair is strong and which is weak
- Predicting extent of reaction using the generalization

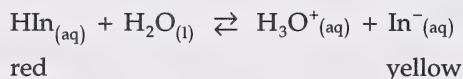
OR

Use the five-step method of analysing Brønsted-Lowry acid-base systems. Add other information where necessary.

Analyse these systems:

- $\text{H}_2\text{PO}_4^-_{(\text{aq})} + \text{H}_2\text{BO}_3^-_{(\text{aq})} \rightleftharpoons$
- ammonium chloride reacts with sodium methanoate ($\text{NaHCOO}_{(\text{aq})}$)

2. Give one reason why the Brønsted-Lowry theory is not considered to be fully comprehensive.
3. a. Indicators are conjugate acid-base pairs. In what way are they uniquely different from all other acid-base conjugate pairs?
- b. What colour would the indicator congo red be in a solution of $\text{pH} = 6$?
4. You are given the general equation

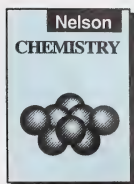


- a. In a strong acid solution, this indicator would be the colour _____.
- b. In a strong base solution, this indicator would be the colour _____.
- c. What would be the colour of the indicator in the colour change range?
- d. Indicate a substance and write the net ionic equation that could cause this equilibrium to shift to the right.
- e. If the colour change range of this indicator occurred between $\text{pH} 9$ and 11 , what could you say about the strength of the acid $\text{HIn}_{(\text{aq})}$? of the base $\text{In}^-_{(\text{aq})}$?
5. Indicators were used to test the pH of two solutions. The following data table summarizes the results.

Indicator	Solution A	Solution B
orange IV	yellow	yellow
phenolphthalein	pink	colourless
bromothymol blue	blue	yellow

Determine whether Solution A is acidic or basic. Is Solution B acidic or basic?

Check your answers by turning to the Appendix, Section 2: Extra Help.

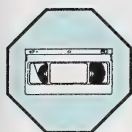


If you would like further practice in working with the concepts presented in this section, answer any of questions 6-9, 17-22, or 26 on pages 497-499 of your textbook. The answers to these questions can be found on pages 519-520 of *Nelson Chemistry*.

Enrichment

Do **one** of the following questions.

- If you have access to the video series *CHEM Study* (Ward's, 2nd ed., 1989), watch the video titled Acid-Base Indicators. In a paragraph, describe how a universal indicator is produced.
- The labels were removed from four flasks containing 0.10 mol/L solutions of $\text{HF}_{(\text{aq})}$, $\text{HCN}_{(\text{aq})}$, $\text{CH}_3\text{COOH}_{(\text{aq})}$, and $\text{HBr}_{(\text{aq})}$. (Assume that the flasks were relabelled A, B, C, and D respectively.) Following is a laboratory procedure that was used to identify each solution.
 - One or two drops of orange IV were added to a sample of each of the four solutions. The colour of each solution was recorded.
 - One or two drops of methyl orange were added to a separate sample of each of the four solutions. The colour of each solution was recorded.
 - Predict the pH of each solution using K_a values (and the K_a approximation) where required.
 - Make a data table and record the expected results for the four solutions tested.
 - Explain how the results will identify each of the four solutions.
- Brønsted-Lowry reactions are very common in your own home kitchen. Investigate five of the following common kitchen practices, and explain each in terms of a balanced Brønsted-Lowry equation.
 - Lemon juice is often sprinkled over fish.
 - Buttermilk pancakes rise in the fry-pan.
 - Baking soda is often placed in the refrigerator to eliminate odours.
 - Vinegar can cause a rise in baked goods.
 - Vegetables stay greener when cooked by steam, rather than in boiling water.
 - Vinegar is often used to remove scale from kettles and pots.
 - Acid-based cleaners are never used for cleaning marble tile or countertops.



Science Skills

- ☒ A. Initiating
- ☐ B. Collecting
- ☐ C. Organizing
- ☒ D. Analysing
- ☐ E. Synthesizing
- ☐ F. Evaluating

Check your answers by turning to the Appendix, Section 2: Enrichment.

Conclusion

In this section you studied the Brønsted-Lowry theory in detail. You discovered that even with the assistance of certain empirical generalizations, its predictive power was sufficiently suspect to require further revision or replacement. The Brønsted-Lowry theory was then used to explain and predict the behaviour of a group of weak conjugate acids and bases known as indicators.

40

Section 2 Assignment: Simplifying Things – Brønsted-Lowry

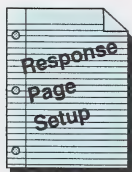
Review the Evaluation information found in the introductory pages of this module.

It is important to number and clearly identify each page with the following information at the top:

Chemistry 30 – Module 6 Section 2 Assignment Page # Name and ID#

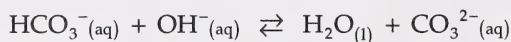
Be sure to write legibly. Leave a wide left margin and number all of your pages.

Part A: Multiple Choice



Read each question carefully and decide which of the choices **best** completes the statement or answers the question. Place the number of each question in a vertical column and place your answer (A, B, C, or D) beside each number. Each question is worth one mark. (Total = 11 marks)

1. Identify the Brønsted-Lowry acids in the following reaction equilibrium:



- A. $\text{CO}_3^{2-}(\text{aq})$ and $\text{OH}^-(\text{aq})$
- B. $\text{HCO}_3^-(\text{aq})$ and $\text{H}_2\text{O}(\text{l})$
- C. $\text{HCO}_3^-(\text{aq})$ and $\text{OH}^-(\text{aq})$
- D. $\text{H}_2\text{O}(\text{l})$ and $\text{CO}_3^{2-}(\text{aq})$

2. In the equilibrium $\text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq}) \rightleftharpoons \text{H}_2\text{CO}_3(\text{aq}) + \text{SO}_4^{2-}(\text{aq})$,

$\text{H}_2\text{CO}_3(\text{aq})$ acts as a Brønsted-Lowry acid because it

- A. liberates free hydrogen ions
- B. donates a proton
- C. accepts a proton
- D. reacts with $\text{H}_2\text{O}(\text{l})$

3.
$$\begin{array}{ccccccc} \text{HA}^-(\text{aq}) & \text{HB}^-(\text{aq}) & \text{HC}(\text{aq}) & \text{HD}(\text{aq}) & & & \\ \hline & & \text{increasing strength of acid} & & \rightarrow & & \end{array}$$

Using the given information, the strongest conjugate base is

- A. $\text{C}^-(\text{aq})$
- B. $\text{A}^{2-}(\text{aq})$
- C. $\text{B}^{2-}(\text{aq})$
- D. $\text{D}^-(\text{aq})$

4. The reaction equilibrium that favours products is

- A. $\text{H}_2\text{CO}_3(\text{aq}) + \text{F}^-(\text{aq}) \rightleftharpoons \text{HF}(\text{aq}) + \text{HCO}_3^-(\text{aq})$
- B. $\text{HS}^-(\text{aq}) + \text{Cl}^-(\text{aq}) \rightleftharpoons \text{HCl}(\text{aq}) + \text{S}^{2-}(\text{aq})$
- C. $\text{HSO}_4^-(\text{aq}) + \text{NO}_2^-(\text{aq}) \rightleftharpoons \text{HNO}_2(\text{aq}) + \text{SO}_4^{2-}(\text{aq})$
- D. $\text{NH}_4^+(\text{aq}) + \text{CN}^-(\text{aq}) \rightleftharpoons \text{NH}_3(\text{aq}) + \text{HCN}(\text{aq})$

5. The net ionic equation for the reaction between solutions of $\text{NaHSO}_4(\text{aq})$ and $\text{NaHCO}_3(\text{aq})$ is

- A. $\text{HSO}_4^-(\text{aq}) + \text{CO}_3^{2-}(\text{aq}) \rightleftharpoons \text{HCO}_3^-(\text{aq}) + \text{SO}_4^{2-}(\text{aq})$
- B. $\text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq}) \rightleftharpoons \text{CO}_3^{2-}(\text{aq}) + \text{H}_2\text{SO}_4(\text{aq})$
- C. $\text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq}) \rightleftharpoons \text{H}_2\text{CO}_3(\text{aq}) + \text{SO}_4^{2-}(\text{aq})$
- D. $\text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq}) \rightleftharpoons \text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq})$

6. The reaction in which the state of equilibrium favours the reactants more than the products is
- $\text{HF}_{(\text{aq})} + \text{HSO}_4^{-}(\text{aq}) \rightleftharpoons \text{H}_2\text{SO}_{4(\text{aq})} + \text{F}^{-}(\text{aq})$
 - $\text{H}_3\text{PO}_{4(\text{aq})} + \text{HS}^{-}(\text{aq}) \rightleftharpoons \text{H}_2\text{PO}_4^{-}(\text{aq}) + \text{H}_2\text{S}_{(\text{aq})}$
 - $\text{H}_2\text{SO}_{3(\text{aq})} + \text{SO}_3^{2-}(\text{aq}) \rightleftharpoons \text{HSO}_3^{-}(\text{aq}) + \text{HSO}_3^{-}(\text{aq})$
 - $\text{CH}_3\text{COOH}_{(\text{aq})} + \text{HCO}_3^{-}(\text{aq}) \rightleftharpoons \text{H}_2\text{CO}_{3(\text{aq})} + \text{CH}_3\text{COO}^{-}(\text{aq})$
7. In the reaction $\text{HSO}_4^{-}(\text{aq}) + \text{NH}_{3(\text{g})} \rightleftharpoons \text{NH}_4^{+}(\text{aq}) + \text{SO}_4^{2-}(\text{aq})$, one conjugate pair is
- $\text{NH}_4^{+}(\text{aq})$ and $\text{HSO}_4^{-}(\text{aq})$
 - $\text{SO}_4^{2-}(\text{aq})$ and $\text{NH}_4^{+}(\text{aq})$
 - $\text{NH}_{3(\text{g})}$ and $\text{SO}_4^{2-}(\text{aq})$
 - $\text{NH}_{3(\text{g})}$ and $\text{NH}_4^{+}(\text{aq})$
8. A weak solution extracted from red cabbage reacts with water according to the following equation: $\text{HRd}_{(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \rightleftharpoons \text{H}_3\text{O}^{+}(\text{aq}) + \text{Rd}^{-}(\text{aq})$. In acidic solutions this substance is red; in basic solutions, it is yellow. A correct inference is that the red substance is
- $\text{H}_3\text{O}^{+}(\text{aq})$
 - $\text{HRd}_{(\text{aq})}$
 - $\text{Rd}^{-}(\text{aq})$
 - $\text{OH}^{-}(\text{aq})$
9. In which of the following solutions would phenolphthalein be red?
- $[\text{OH}^{-}(\text{aq})] = 10^{-3} \text{ mol/L}$
 - $[\text{H}_3\text{O}^{+}(\text{aq})] = 10^{-4} \text{ mol/L}$
 - $[\text{H}_3\text{O}^{+}(\text{aq})] = 10^{-6} \text{ mol/L}$
 - $[\text{OH}^{-}(\text{aq})] = 10^{-11} \text{ mol/L}$

10. A solution of sodium acetate, $\text{NaCH}_3\text{COO}_{(\text{aq})}$, turns red litmus paper blue because
- acetate solutions are acidic
 - solid sodium acetate contains $\text{OH}^-_{(\text{aq})}$
 - water molecules donate $\text{H}^+_{(\text{aq})}$ to $\text{CH}_3\text{COO}^-_{(\text{aq})}$
 - water molecules donate $\text{OH}^-_{(\text{aq})}$ to $\text{CH}_3\text{COO}^-_{(\text{aq})}$
11. A solution was divided equally among five test tubes. Each solution sample was tested using various indicators and the results were recorded as shown.

Test Tube	Indicator Added	Colour of Solution
1	orange IV	yellow
2	methyl orange	yellow
3	bromocresol green	blue
4	methyl red	orange
5	bromothymol blue	yellow

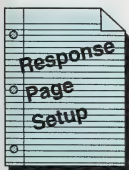
The pH range of the solution is

- 3.0 to 4.0
- 4.0 to 5.0
- 5.0 to 6.0
- 6.0 to 7.0

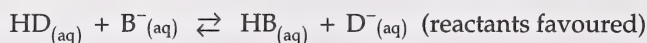
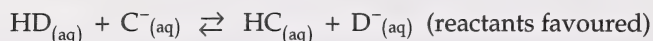
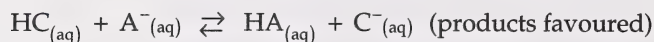
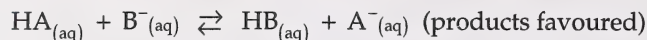
Part B: Written Response

Write your answers neatly and concisely. For full marks, your answers must show all pertinent explanations, calculations, and formulas.

12. Write the Brønsted-Lowry net ionic equation for each of the following reactions. Predict whether reactants or products are favoured at equilibrium.
- A solution of lithium acetate is added to a solution of ammonium bromide. (2 marks)
 - A student mixes a calcium hydrogen phosphate solution with ethanoic acid. (2 marks)
 - A solution of hydrobromic acid reacts with an ammonia solution. (2 marks)



13. Analyse the following data. List the acids in order of increasing strength (weakest to strongest). (4 marks)



14. If the $[\text{OH}^{-}_{(\text{aq})}]$ of a solution changes from 10^{-1} mol/L to 10^{-3} mol/L, what will be the colour change response of the indicator indigo carmine? Explain your reasoning. (2 marks)
15. Match each of the statements in Column 1 to the appropriate statement from Column 2. (9 marks)

Column 1

Column 2

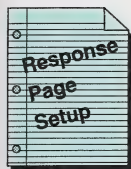
- | | |
|---|---|
| a. conjugate pair | i. indigo carmine |
| b. indicator is red at pH = 11 | ii. solution is yellow |
| c. amphiprotic substance | iii. $\text{OH}^{-}_{(\text{aq})}$ |
| d. strong attraction for protons | iv. methyl violet |
| e. acid above base – >50% reaction | v. $\text{H}_2\text{SO}_{4(\text{aq})} - \text{SO}_4^{2-}_{(\text{aq})}$ |
| f. bromothymol blue in 0.10 mol/L $\text{HCl}_{(\text{aq})}$ solution | vi. $\text{HSO}_4^{-}_{(\text{aq})}$ |
| g. is green during colour change range | vii. phenolphthalein |
| h. is the strongest acid on the indicator chart | viii. Brønsted-Lowry acid |
| i. is limited to aqueous solutions | ix. a useful generalization |
| | x. Brønsted-Lowry theory |
| | xi. solution is blue |
| | xii. $\text{H}_3\text{PO}_{4(\text{aq})} - \text{H}_2\text{PO}_4^{-}_{(\text{aq})}$ |
| | xiii. Arrhenius theory |

16. a. Write two net ionic equations that correctly illustrate the role of the hydrogen sulphite ion as an amphiprotic substance, using perchloric acid and the dihydrogen borate ion as reacting partners. Indicate, under each equation, which reactants and products are acids and which are bases. **(4 marks)**
- b. List the conjugate acid-base pairs for each reaction. **(2 marks)**
- c. Predict whether reactants or products are favoured for each reaction. **(2 marks)**

Write each required equation as follows:

Equation 1: Use the perchloric acid reaction.

Equation 2: Use the dihydrogen borate ion reaction.



MODULE SUMMARY

In this module, you reinforced your knowledge of science process. You saw that science is not a black-and-white affair producing a tidy body of knowledge, but rather, a creative human activity requiring hard work and patience. You were introduced to a number of theoretical definitions of acids and bases. You learned about their advantages and limitations, and that all good working theories evolve by the continuous revision of scientific ideas. You concluded with a detailed study of the Brønsted-Lowry theory of acids and bases. This theory became the foundation for an understanding of the behaviour of acid-base equilibria and indicators. Acids and bases are not only ubiquitous – they also proved to be a challenge.

35

Final Module Assignment

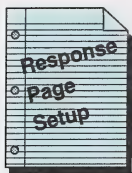
Review the Evaluation information found in the introductory pages of this module.

It is important to number and clearly identify each page with the following information at the top:

Chemistry 30 – Module 6 Final Module Assignment Page # Name and ID#

Be sure to write legibly. Leave a wide left margin and number all of your pages.

Part A: Multiple Choice



Read each question carefully and decide which of the choices **best** completes the statement or answers the question. Place the number of each question in a vertical column and place your answer (A, B, C, or D) beside each number. Each question is worth one mark. **(Total = 8 marks)**

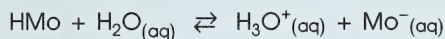
- A substance is an Arrhenius acid if it
 - turns phenolphthalein solution red
 - ionizes in water to form hydrogen ions
 - turns litmus paper blue
 - reacts with water to form hydrogen ions
- When orange IV and bromocresol green are added to a solution with a pH of 3.00, the resulting solution colour would be
 - orange
 - green
 - blue
 - yellow
- An acid-base reaction that does NOT favour formation of products is
 - $\text{F}^{-}(\text{aq}) + \text{HCO}_3^{-}(\text{aq}) \rightleftharpoons$
 - $\text{HNO}_{2(\text{aq})} + \text{HCO}_3^{-}(\text{aq}) \rightleftharpoons$
 - $\text{HS}^{-}(\text{aq}) + \text{HSO}_4^{-}(\text{aq}) \rightleftharpoons$
 - $\text{HSO}_3^{-}(\text{aq}) + \text{HOOC}\text{COOH}_{(\text{aq})} \rightleftharpoons$
- The balanced net ionic equation for the reaction that occurs when hydrocyanic acid is mixed with aqueous barium hydroxide solution is
 - $2 \text{HCN}_{(\text{aq})} + \text{Ba}(\text{OH})_{2(\text{aq})} \rightleftharpoons 2 \text{H}_2\text{O}_{(\text{l})} + \text{Ba}(\text{CN})_{2(\text{aq})}$
 - $\text{HCN}_{(\text{aq})} + \text{OH}^{-}(\text{aq}) \rightleftharpoons \text{H}_2\text{O}_{(\text{aq})} + \text{CN}^{-}(\text{aq})$
 - $\text{H}_3\text{O}^{+}(\text{aq}) + \text{OH}^{-}(\text{aq}) \rightleftharpoons 2 \text{H}_2\text{O}_{(\text{l})}$
 - $2 \text{HCN}_{(\text{aq})} + \text{OH}^{-}(\text{aq}) \rightleftharpoons 2 \text{CN}^{-}(\text{aq}) + \text{H}_2\text{O}_{(\text{l})}$

5. Which of the following is an Arrhenius base?

- A. $\text{NH}_3(\text{aq})$
- B. $\text{CN}^-(\text{aq})$
- C. $\text{Ca}(\text{OH})_2(\text{aq})$
- D. $\text{BaO}(\text{aq})$

Use the following information to answer questions 6 and 7.

- The equilibrium reaction for the indicator methyl orange is



- Methyl orange exhibits the following colours in solution at the $[\text{H}_3\text{O}^+_{(\text{aq})}]$ indicated.

Colour	red	red	red	orange	yellow	yellow	yellow	yellow
$[\text{H}_3\text{O}^+_{(\text{aq})}]$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}

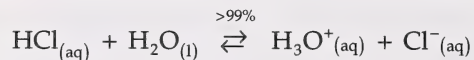
6. The yellow colour is visible because of the presence of

- A. $\text{H}_3\text{O}^+_{(\text{aq})}$
- B. HMo
- C. $\text{H}_2\text{O}_{(\text{aq})}$
- D. $\text{Mo}^-_{(\text{aq})}$

7. Which of the following 0.10 mol/L solutions would be yellow if several drops of $\text{HMo}_{(\text{aq})}$ were added?

- A. $\text{HF}_{(\text{aq})}$
- B. $\text{HCN}_{(\text{aq})}$
- C. $\text{CH}_3\text{COOH}_{(\text{aq})}$
- D. $\text{HBr}_{(\text{aq})}$

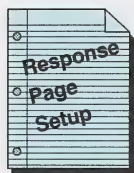
8. The following proton transfer reaction goes to completion:



This is because

- A. $\text{H}_2\text{O}_{(\text{l})}$ acts as a stronger base than $\text{H}_3\text{O}^+_{(\text{aq})}$
- B. $\text{HCl}_{(\text{aq})}$ acts as a stronger acid than $\text{H}_3\text{O}^+_{(\text{aq})}$
- C. $\text{H}_2\text{O}_{(\text{l})}$ acts as a weaker base than $\text{Cl}^-_{(\text{aq})}$
- D. $\text{HCl}_{(\text{aq})}$ acts as a weaker base than $\text{Cl}^-_{(\text{aq})}$

Part B: Numerical Response



Read each question carefully. Record only your final answer by writing it in a four-box unit similar to the following:

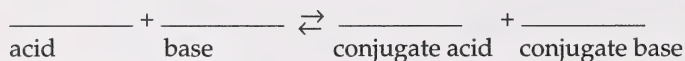
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Enter the first digit of your answer in the left-hand box and leave any unused boxes blank. If a decimal point occurs in your answer, it should occupy its own box.

Use the following information to answer question 9.

1. $\text{NH}_4^+_{(\text{aq})}$	4. $\text{OH}^-_{(\text{aq})}$
2. $\text{Cl}^-_{(\text{aq})}$	5. $\text{NH}_3_{(\text{aq})}$
3. $\text{Na}^+_{(\text{aq})}$	6. $\text{H}_2\text{O}_{(\text{l})}$

9. Solutions of ammonium chloride and sodium hydroxide are mixed together. The net ionic equation that represents the acid-base reaction that occurs is outlined here. The reactants and products in the order stated, as selected from the given numbered species, would be



Record the four digits in the boxes on your response sheet. (1 mark)

Use the following information to answer question 10.

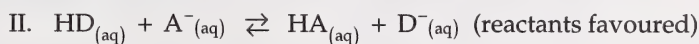
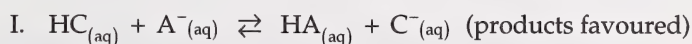
Solution	INDICATORS AND COLOURS		
	phenolphthalein	indigo carmine	methyl orange
1	colourless	blue	red
2	red	yellow	yellow
3	colourless	blue	yellow
4	pink	blue	yellow

10. When these solutions are arranged from highest to lowest pH value, their numerical sequence is _____. (Record all four digits in the boxes on your response sheet.) (1 mark)

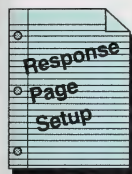
Part C: Written Response

Write your answers neatly and concisely. For full marks, your answers must show all pertinent explanations, calculations, and formulas.

11. Use the five-step method of predicting acid-base reactions to write net ionic equations for the following reactants. Indicate whether reactants or products are favoured at equilibrium.
- A solution of sodium dihydrogen phosphate reacts with a solution of potassium hydrogen oxalate. (2 marks)
 - Hydroiodic acid is added to a solution of sodium cyanide. (2 marks)
 - A dilute solution of yellow bromothymol blue is added to a solution of lithium hydrogen carbonate. (2 marks)
12. What will be the colour of the reaction solution in 11.c? Explain. (1 mark)
13. Three hypothetical acids, $\text{HA}_{(\text{aq})}$, $\text{HC}_{(\text{aq})}$, and $\text{HD}_{(\text{aq})}$ were tested. The following data was obtained.



- Based on this data, list the three acids from strongest to weakest. (1 mark)
- Which species would be the weakest conjugate base? (1 mark)

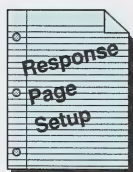


14. A student checked five unknown solutions for conductivity and indicator properties in an effort to determine which solution was 0.10 mol/L sodium acetate. The results are listed in the following table.

Science Skills	
☐	A. Initiating
☐	B. Collecting
☐	C. Organizing
☒	D. Analysing
☐	E. Synthesizing
☐	F. Evaluating

Solution	Electrical Conductivity	Chlorophenol Red
I	high	yellow
II	high	orange
III	low	orange
IV	high	red
V	low	red

- Write a balanced net ionic equation describing the reaction between sodium acetate and water. (1 mark)
- Explain how the results of the electrical conductivity tests contributed to the identification of the sodium acetate solution. (1 mark)
- Explain how the results of the indicator colour test contribute to the identification of the sodium acetate solution. (1 mark)
- The sodium acetate solution is Solution _____. (1 mark)



Reproduce the science skills assessment box after your response to this question. Remember to indicate your evaluation of your skill level for each identified science skill. Leave a space for the teacher assessment.

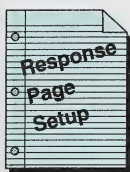
Self: A.	☐	B.	☐	C.	☐	D.	☐	E.	☐	F.	☐
Teacher: A.	☐	B.	☐	C.	☐	D.	☐	E.	☐	F.	☐

Science Skills	
☐	A. Initiating
☐	B. Collecting
☒	C. Organizing
☒	D. Analysing
☒	E. Synthesizing
☐	F. Evaluating

15. A lab technician prepared 0.10 mol/L solutions of hydroiodic acid and acetic acid and forgot to label them. In an attempt to visually confirm the identity of the solutions, the technician labelled them Solution A (actually the $\text{HI}_{(\text{aq})}$) and Solution B (actually the $\text{CH}_3\text{COOH}_{(\text{aq})}$), and performed the following experiment.

- A volume of 2.0 mL of each sample was placed into separate test tubes.
- Three drops of methyl orange were added to each sample and the colour of each resulting solution was recorded.
- A volume of 2.0 mL of each sample was placed into another set of test tubes.
- Three drops of orange IV were added to each sample and the colour of each resulting solution was recorded.

- Calculate the theoretical pH of each of the 0.10 mol/L acid samples. Show your work. **(4 marks)**
- Construct a data table and insert the expected observations for the two solutions once the indicators were added. **(2 marks)**
- Briefly explain how the results help to identify the acids. **(2 marks)**



Reproduce the science skills assessment box after your response to this question. Remember to indicate your evaluation of your skill level for each identified science skill. Leave a space for the teacher assessment.

Self: A.	☐	B.	☐	C.	☐	D.	☐	E.	☐	F.	☐
Teacher: A.	☐	B.	☐	C.	☐	D.	☐	E.	☐	F.	☐

Part D: True or False

- For each of the following statements (a-h), write the word *true* or the word *false* as your answer, based on the information given. **(1/2 mark each; Total = 4 marks)**
 - $\text{HTe}^-_{(\text{aq})}$ is an amphoteric substance.
 - The modified Arrhenius theory introduced the concept of the free $\text{H}^+_{(\text{aq})}$ ion.
 - Strong acids give rise to weaker conjugate bases.
 - When $\text{KHSO}_{4(\text{aq})}$ reacts with $\text{KNO}_{2(\text{aq})}$, reactants are favoured at equilibrium.
 - $\text{SO}_{2(\text{g})}$ is an example of an acid according to the oxygen theory.
 - In a solution of pH 6, congo red will be red in colour.
 - The Brønsted-Lowry theory cannot predict the strength of an acid.
 - Chlorophenol red is a stronger acid than orange IV.

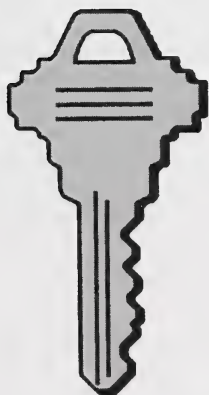
To ensure that all of your work has been completed in a satisfactory manner, check off the items in the following list:

- ☐ Section 1 Assignment has been completed.
- ☐ Section 2 Assignment has been completed.
- ☐ Final Module Assignment has been completed.
- ☐ Your responses are organized and neat, with room for teacher comments.
- ☐ All your response pages are numbered consecutively and identified with this heading.

Chemistry 30 – Module 6 Section # Assignment Page # Name and ID #

Submit **only** your **assignment response pages** for evaluation.

Appendix



Glossary
Suggested Answers

Glossary

acid-base indicators: substances that change colour when reacted with acids or bases

conjugate acid-base pair: a pair of substances that differ only by a proton

hydronium ion: a hydrated hydrogen ion

neutralize: to eliminate the acidic or basic properties of the partner reactant

Suggested Answers

Section 1: Activity 1

- | Scientist | Theory | Main Feature of Theory | Reason Theory Was Discarded |
|--|-----------------|--------------------------------------|--|
| Antoine Lavoisier | Oxygen Theory | All acids contain oxygen. | It has too many exceptions. <ul style="list-style-type: none"> Not all oxides produce acids. Some acids do not contain oxygen. |
| Sir Humphry Davy and Justus von Liebig | Hydrogen Theory | All acids are compounds of hydrogen. | It does not explain why only certain hydrogen compounds are acids (many are neutral or basic). |
- A base is a substance that dissociates in aqueous solution to produce hydroxide ions.
 - An acid is a substance that ionizes in aqueous solution to produce hydrogen ions.
- Arrhenius assumed that the water somehow caused the acid molecules to ionize, but did not explain how. Water had no active role to play other than to provide a passive medium in which the hydrogen ions and hydroxide ions could exist.
- Neutralization occurs when an $\text{H}^+(\text{aq})$ ion from the acid and an $\text{OH}^-(\text{aq})$ ion from the base combine to form water.
- Neutral solutions are those in which no $\text{H}^+(\text{aq})$ or $\text{OH}^-(\text{aq})$ ions are formed, or are present.
- $\text{HCl}_{(\text{aq})} \rightarrow \text{H}^+(\text{aq}) + \text{Cl}^-(\text{aq})$
 - $\text{HNO}_{3(\text{aq})} \rightarrow \text{H}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$
 - $\text{KOH}_{(\text{aq})} \rightarrow \text{K}^+(\text{aq}) + \text{OH}^-(\text{aq})$
 - $\text{CH}_3\text{COOH}_{(\text{aq})} \rightarrow \text{H}^+(\text{aq}) + \text{CH}_3\text{COO}^-(\text{aq})$
 - $\text{Ba}(\text{OH})_{2(\text{aq})} \rightarrow \text{Ba}^{2+}(\text{aq}) + 2 \text{OH}^-(\text{aq})$

7. Neutral electrolytic solutes produced ions (other than $\text{H}^+(\text{aq})$ and $\text{OH}^-(\text{aq})$) in solution. Neutral non-electrolytic solutes produced molecules in solution.
8. Here are some possible predictions. These predictions are made strictly within the confines of the Arrhenius theory of acids and bases, taking major clues from the ions present in solution.

Substance in Solution (0.10 mol/L)	Chemical Formula	Form in Solution	Prediction (acid, base, neutral)
hydrogen chloride	HCl	$\text{H}^+(\text{aq}), \text{Cl}^-(\text{aq})$	acid
sodium carbonate (soda ash)	Na_2CO_3	$2 \text{Na}^+(\text{aq}), \text{CO}_3^{2-}(\text{aq})$	neutral
sodium hydrogen carbonate	NaHCO_3	$\text{Na}^+(\text{aq}), \text{HCO}_3^-(\text{aq})$	neutral
sodium hydrogen sulphate	NaHSO_4	$\text{Na}^+(\text{aq}), \text{HSO}_4^-(\text{aq})$	neutral
sodium hydroxide (lye)	NaOH	$\text{Na}^+(\text{aq}), \text{OH}^-(\text{aq})$	base
calcium hydroxide (saturated)	$\text{Ca}(\text{OH})_2$	$\text{Ca}^{2+}(\text{aq}), 2 \text{OH}^-(\text{aq})$	base
carbon dioxide	CO_2	$\text{CO}_2(\text{aq})$	neutral
magnesium oxide (saturated)	MgO	$\text{Mg}^{2+}(\text{aq}), \text{O}^{2-}(\text{aq})$	neutral
ammonia	NH_3	$\text{NH}_3(\text{aq})$	neutral
hydrogen acetate (vinegar)	CH_3COOH	$\text{H}^+(\text{aq}), \text{CH}_3\text{COO}^-(\text{aq})$	acid
water	H_2O	$\text{H}_2\text{O}(\text{l})$	neutral

9. A possible experimental design is as follows:

Various substances of equal concentration are systematically tested for properties of acids and bases using conductivity and reaction with litmus paper as parameters. The manipulated variable is the substance tested; the responding variables are the degree of conductivity and litmus paper colour; the controlled variables are the concentration and temperature. Pure water is used as a control.

10. A suggested procedure could be as follows:

- Test each solution with a conductivity apparatus and record the results in the data table.
- Test each solution with both red and blue litmus paper and record the results in the data table.
- Test the distilled water with the conductivity tester and both red and blue litmus paper. Record the results in the data table.

11. Your evidence should be similar to the following:

Substance in Solution (0.10 mol/L)	Conducts Electricity	Blue Litmus	Red Litmus
hydrogen chloride	yes	red	red
sodium carbonate (soda ash)	yes	blue	blue
sodium hydrogen carbonate	yes	blue	blue
sodium hydrogen sulphate	yes	red	red
sodium hydroxide (lye)	yes	blue	blue
calcium hydroxide (saturated)	yes	blue	blue
carbon dioxide	yes	red	red
magnesium oxide (saturated)	yes	blue	blue
ammonia	yes	blue	blue
hydrogen acetate (vinegar)	yes	red	red
water	no	blue	red

12. The evidence summary should look as follows:

SUMMARY DATA TABLE

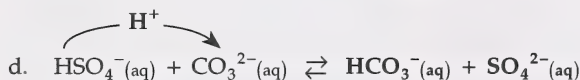
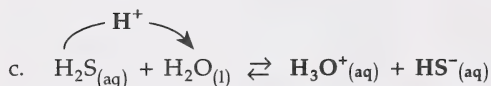
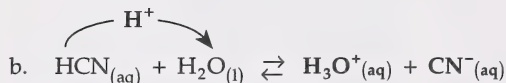
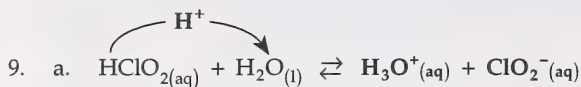
Substance in Solution (0.10 mol/L)	Electrolyte (Yes or No)	Predicted Property	Actual Property
hydrogen chloride	yes	acidic	acidic
sodium carbonate (soda ash)	yes	neutral	basic
sodium hydrogen carbonate	yes	neutral	basic
sodium hydrogen sulphate	yes	neutral	acidic
sodium hydroxide (lye)	yes	basic	basic
calcium hydroxide (saturated)	yes	basic	basic
carbon dioxide	yes	neutral	acidic
magnesium oxide (saturated)	yes	neutral	basic
ammonia	yes	neutral	basic
hydrogen acetate (vinegar)	yes	acidic	acidic
water	no	neutral	neutral

13.
 - a. The Arrhenius theory predicted that two substances would be acidic.
 - b. Four substances actually tested acidic.
 - c. The Arrhenius theory predicted that six substances would be neutral.
 - d. None of the substances tested were neutral in solution, except water.
 - e. The Arrhenius theory predicted that two substances would be basic.
 - f. Six substances actually tested basic.
14. There are no common features shared by substances that were not successfully predicted by the Arrhenius theory. No valid conclusion can be drawn.
15. The data seems to support the idea of acids and bases being electrolytes. However, there were no non-electrolyte substances tested for acid-base properties. This would further support or refute the idea.
16. The Arrhenius theory correctly predicted only two of a possible four acid solutions (50% accuracy). It also predicted only two of a possible six basic solutions (33% accuracy). It is not very successful.
17. See page 519 in *Nelson Chemistry* for the answers to textbook review questions 1, 2, and 3.

Section 1: Activity 2

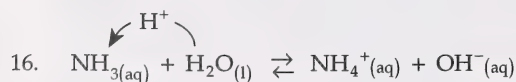
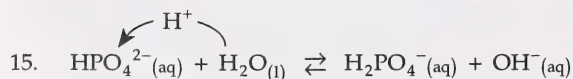
1. A good working theory should be able to explain empirical behaviours and predict the results of new experiments.
2. Two key ideas that led to a revision of the Arrhenius theory were
 - Collisions between water molecules and hydrogen ions are likely to occur.
 - The nature of the hydrogen ion is such that it is not likely to remain alone or unreacted in solution.
3. There is no evidence of unhydrated (free) hydrogen ions in solution.
4. The hydrogen ion (a proton) is a highly charged positive particle and is likely to be attracted to the negative end of a polar water molecule.
5. The water molecule is fairly polar, and is likely to attract a positive charge to the negative end of its dipole.
6. The hydronium ion (also called a hydrated proton) is the proposed particle.
7. The hydrogen ion transfers from the $\text{HSO}_3^-(\text{aq})$ ion to the $\text{H}_2\text{O}(\text{l})$ molecule. The water molecule **gains** a **positive** charge to become a $\text{H}_3\text{O}^+(\text{aq})$ ion. As the H^+ leaves, the $\text{HSO}_3^-(\text{aq})$ ion **loses** a **positive** charge to become a $\text{SO}_3^{2-}(\text{aq})$ ion.

8. During this hydrogen ion transfer, the sulphite ion **gains a positive** charge to become a $\text{HSO}_3^-(\text{aq})$ ion. When the H^+ ion leaves, the $\text{HPO}_4^{2-}(\text{aq})$ ion **loses a positive** charge to become a $\text{PO}_4^{3-}(\text{aq})$ ion.



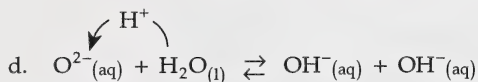
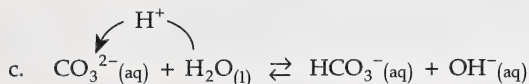
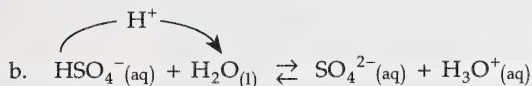
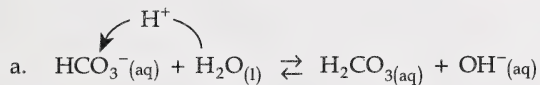
Note: You will notice that only one H^+ ion transfers at a time (in each reaction).

10. Paul Giguère of the Université Laval, Quebec, provided clear experimental evidence for the existence of the hydronium ion in solution. He analysed the results of passing infrared light through solutions of acids.
11. Acidic solutions form when substances react with water to form hydronium ions.
12. $\text{HNO}_3(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons \text{H}_3\text{O}^+(\text{aq}) + \text{NO}_3^-(\text{aq})$
13. $\text{SO}_2(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons \text{H}_2\text{SO}_3(\text{aq})$
 $\text{H}_2\text{SO}_3(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons \text{H}_3\text{O}^+(\text{aq}) + \text{HSO}_3^-(\text{aq})$
14. Basic solutions are formed when substances react with water to form hydroxide ions.

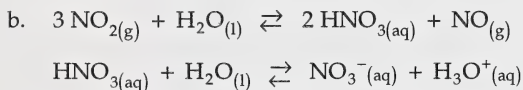
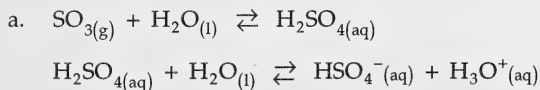


17. The answers to the preceding three questions illustrate how the revision of the Arrhenius theory can *explain* existing acid-base behaviour, but the answers do not predict those behaviours.

18. Textbook question 1:



Textbook question 2:



Note: A reference for this reaction sequence can be found on page 96 of *Nelson Chemistry*.

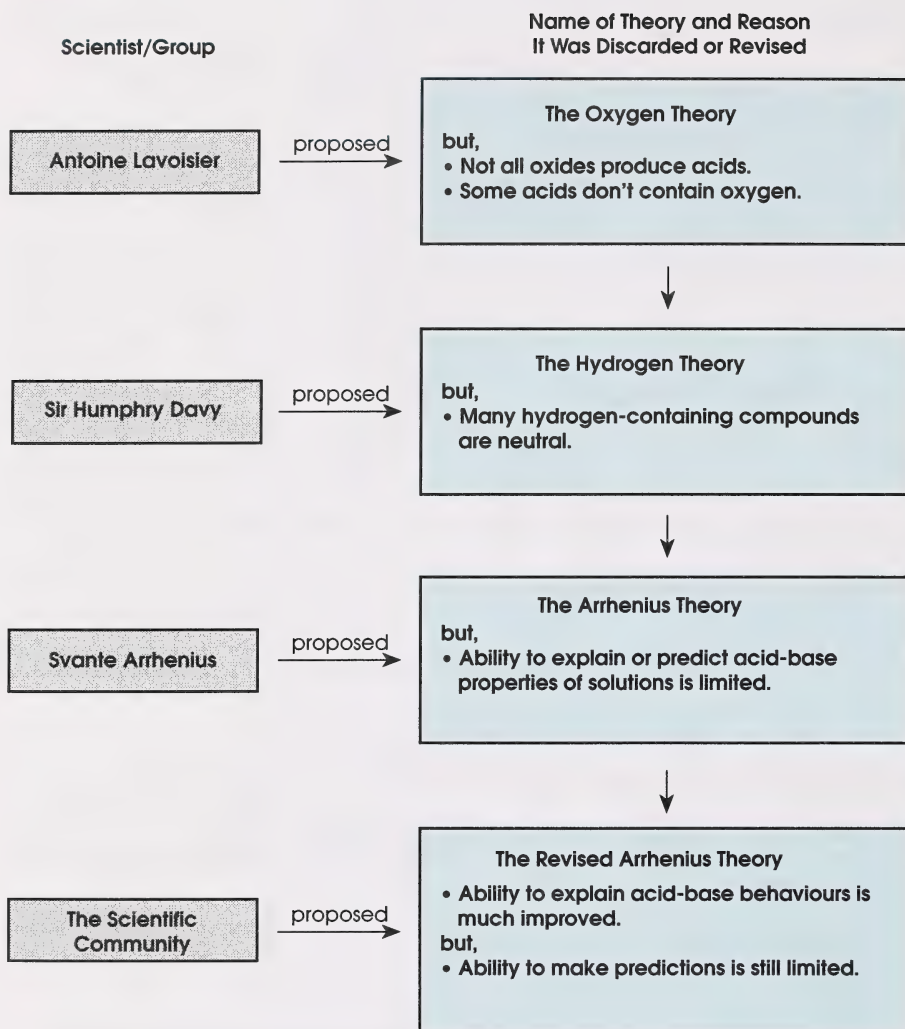
- c. Nitrogen oxides are produced in high temperature combustion reactions, such as those that occur in automobile engines. Sulphur oxides are produced by smelting sulphide ores and burning fossil fuels that contain traces of sulphur.
- d. Emissions may be controlled by improving the technology, such as more efficient catalytic converters and $\text{SO}_{2(\text{g})}$ scrubbers.

19. The modified Arrhenius theory explains the acid or base behaviour of many more substances than the Arrhenius theory did, but it still fails to predict acid-base behaviour.

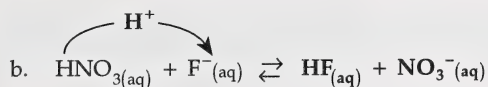
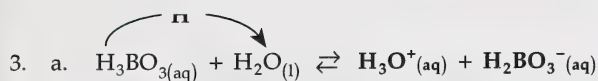
Section 1: Follow-up Activities

Extra Help

1.



2. a. B d. RA g. RA j. A m. RA
b. RA e. B h. RA k. RA
c. A f. A i. A l. B



Enrichment

- Answers will vary. You should expand on the quotation by addressing the process skills you have examined in the light of acid-base theory. In the body of the text, mention should be made of
 - observing
 - inferring
 - experimenting
 - interpreting data
 - defining empirically
 - predicting
 - measuring
 - classifying
 - controlling variables
 - formulating hypotheses
- Testing by attempted falsification was central to Popper's view of science. Scientific theory which is derived using scientific induction can never be proven, but it can be disproven by one repeated negative result. Rather than trying to prove a hypothesis correct, this principle suggests trying to prove it wrong by one negative result. For example, rather than trying to prove something is an acid because of a long list of behaviours, you prove that it is not an acid because it fails to behave as an acid in one area.
 - Popper applied this principle to the social sciences in his criticisms of totalitarian political systems. In Popper's view, a political or social system is like a scientific theory. Therefore the system should be tested by showing where it is failing, not where it is succeeding. Only in these types of social democracies where people are free to criticize the system will the mistakes be corrected.
 - Criticism should be actively encouraged and welcomed. Only through criticism will people see a need for improvement.
- Your investigation can follow the same design and procedure as Investigation 15.1 which you performed in this section. Your evidence should be similar to the following:

Substance	Conductivity	Red Litmus	Blue Litmus
Na_2HPO_4	yes	blue	blue
NaHSO_3	yes	red	red
NH_3	yes	blue	blue
Na_2CO_3	yes	blue	blue
CH_3COOH	yes	red	red

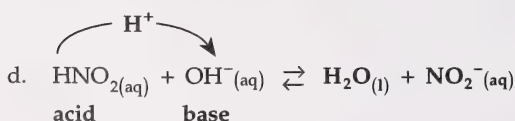
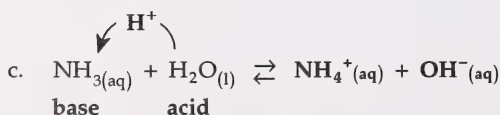
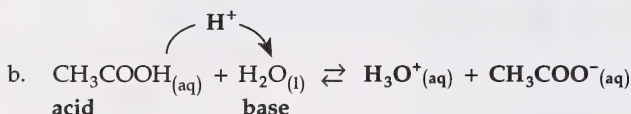
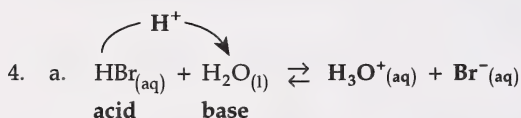
Your predicted and actual results, after analysis, should look like the following:

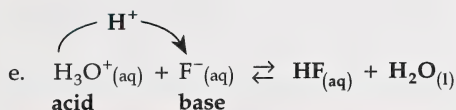
Substance	Predicted Results	Actual Results
Na_2HPO_4	acid or base	base
NaHSO_3	acid or base	acid
NH_3	base	base
Na_2CO_3	base	base
CH_3COOH	acid	acid

The Arrhenius definition predicted the acid behaviour of acetic acid only. The revised theory can predict the behaviour of all except the amphiprotic substances – substances that can act as either an acid or a base. Once the results of the test are clear, the revised theory can explain those results, but it cannot predict them.

Section 2: Activity 1

- Early investigators based their theories on **the acidic or basic properties of the aqueous solutions of acids and bases**, whereas Brønsted and Lowry focused on **the role of an acid and a base in a specific chemical reaction**.
- A Brønsted-Lowry acid is a **proton donor**.
- A Brønsted-Lowry base is a **proton acceptor**.





5.

Strong Acids	Weak Acids
• weak attraction for protons • donate protons readily	• stronger attraction for protons • donate protons less readily

6.

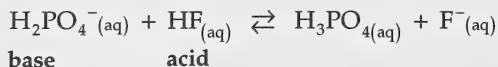
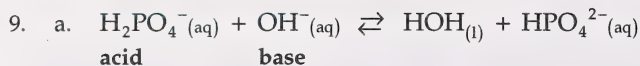
Strong Bases	Weak Bases
• strong attraction for protons • accepts protons readily	• weaker attraction for protons • accept protons less readily

7. a.

Acid	Formula	Percent Reaction (%)	Equilibrium Constant (K_a)
hydroiodic acid	$\text{HI}_{(\text{aq})}$	100	3.2×10^9
hydrogen sulphate ion	$\text{HSO}_4^-_{(\text{aq})}$	27	1.0×10^{-2}
benzoic acid	$\text{C}_6\text{H}_5\text{COOH}_{(\text{aq})}$	—*	6.3×10^{-5}
ethanoic (acetic) acid	$\text{CH}_3\text{COOH}_{(\text{aq})}$	1.3	1.8×10^{-5}
hydrosulphuric acid	$\text{H}_2\text{S}_{(\text{aq})}$	0.10	1.1×10^{-7}
ammonium ion	$\text{NH}_4^+_{(\text{aq})}$	0.0076	5.8×10^{-10}
hydrogen carbonate ion	$\text{HCO}_3^-_{(\text{aq})}$	0.0022	4.7×10^{-11}
hydrogen borate ion	$\text{HBO}_3^{2-}_{(\text{aq})}$	0.000 040	1.6×10^{-14}

*Check the note at the bottom of the Acids and Bases table on page 553 of *Nelson Chemistry*.

- b. As the acids get weaker, the percent reactions and the equilibrium constants get smaller. The decrease in percent reactions is a reflection of the decreasing ability to donate protons to the water molecules. The decrease in K_a reflects a decrease in the value of the product-to-reactant ratio of the equilibrium constant.
8. According to Brønsted-Lowry acid-base theory, some substances can act as an acid in some circumstances or as a base in other circumstances. These substances are called **amphiprotic substances**.



b. The amphiprotic substance in part a. is $\text{H}_2\text{PO}_4^- (\text{aq})$.

10. a. The amphiprotic substances listed in the table are as follows:

- | | |
|----------------------------|--------------------------|
| • hydrogen sulphate ion | • hydrogen phosphate ion |
| • hydrogen oxalate ion | • dihydrogen borate ion |
| • dihydrogen phosphate ion | • hydrogen sulphide ion |
| • hydrogen sulphite ion | • hydrogen borate ion |
| • hydrogen carbonate ion | • water |

b. They are all hydrogen-containing polyatomic ions, except for water.

11. a. An amphiprotic substance will act as an acid if it is a **better proton donor than the substance with which it is reacting.**

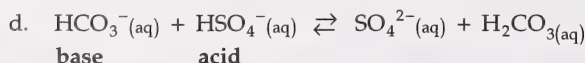
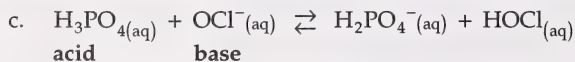
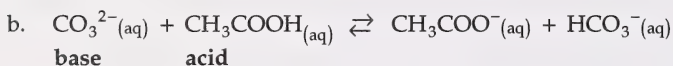
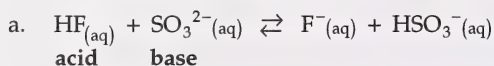
b. An amphiprotic substance will act as a base if it is a **better proton acceptor than the substance with which it is reacting.**

12. The Brønsted-Lowry theory still does not explain why a proton is donated or accepted.

13. A Brønsted-Lowry neutralization is a competition for protons that results in a proton transfer from the strongest acid present to the strongest base present.



15. **Textbook question 7:**



Textbook question 8:

- a. $\text{HCO}_3^-(\text{aq}) + \text{OH}^-(\text{aq}) \rightleftharpoons \text{CO}_3^{2-}(\text{aq}) + \text{H}_2\text{O}(\text{l})$
 acid base
- b. $\text{HCO}_3^-(\text{aq}) + \text{H}_3\text{O}^+(\text{aq}) \rightleftharpoons \text{H}_2\text{CO}_3(\text{aq}) + \text{H}_2\text{O}(\text{l})$
 base acid

Textbook question 9:

The Brønsted-Lowry theory does not require that acid-base reactions be in aqueous solution.

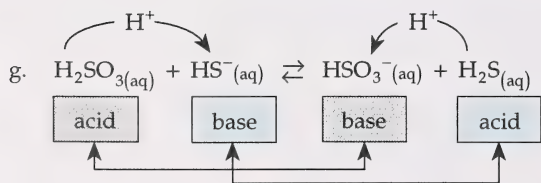
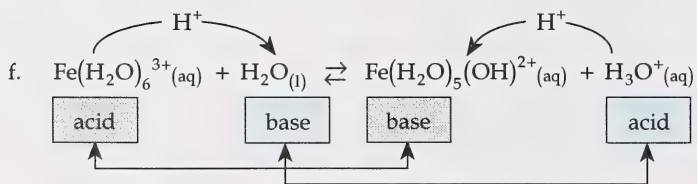
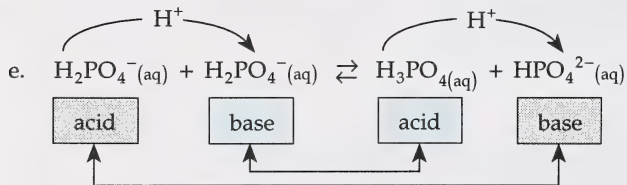
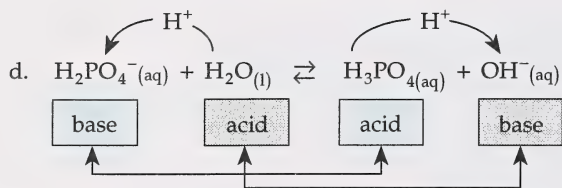
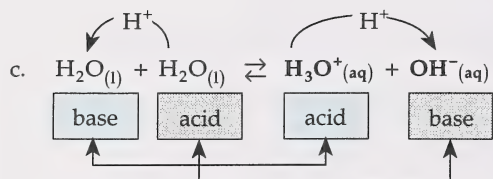
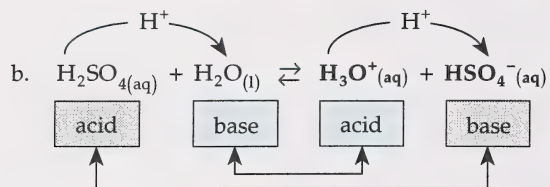
16. A conjugate acid-base pair is a pair of substances that differ only by one proton (H^+).
17. The conjugate bases are given in the following chart:

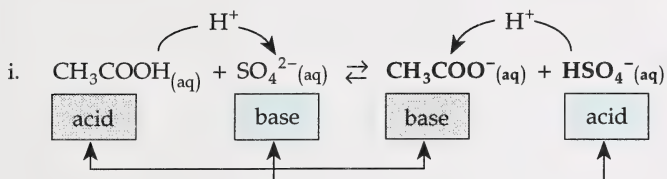
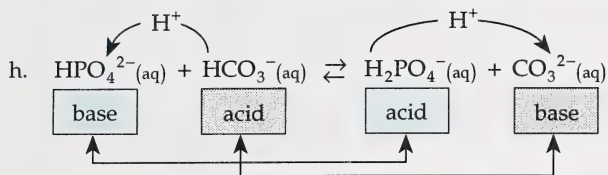
Acid	Conjugate Base	Acid	Conjugate Base
$\text{HCl}(\text{aq})$	$\text{Cl}^-(\text{aq})$	$\text{NH}_4^+(\text{aq})$	$\text{NH}_3(\text{aq})$
$\text{H}_2\text{SO}_4(\text{aq})$	$\text{HSO}_4^-(\text{aq})$	$\text{H}_2\text{O}(\text{l})$	$\text{OH}^-(\text{aq})$
$\text{HCO}_3^-(\text{aq})$	$\text{CO}_3^{2-}(\text{aq})$	$\text{H}_2\text{CO}_3(\text{aq})$	$\text{HCO}_3^-(\text{aq})$
$\text{H}_2\text{PO}_4^-(\text{aq})$	$\text{HPO}_4^{2-}(\text{aq})$	$\text{HOOC}\text{COOH}(\text{aq})$	$\text{HOOC}\text{COO}^-(\text{aq})$

18. The conjugate acids are given in the following chart:

Base	Conjugate Acid	Base	Conjugate Acid
$\text{Br}^-(\text{aq})$	$\text{HBr}(\text{aq})$	$\text{HO}_2^-(\text{aq})$	$\text{H}_2\text{O}_2(\text{aq})$
$\text{NO}_2^-(\text{aq})$	$\text{HNO}_2(\text{aq})$	$\text{HS}^-(\text{aq})$	$\text{H}_2\text{S}(\text{aq})$
$\text{PO}_4^{3-}(\text{aq})$	$\text{HPO}_4^{2-}(\text{aq})$	$\text{HCO}_3^-(\text{aq})$	$\text{H}_2\text{CO}_3(\text{aq})$
$\text{HSO}_4^-(\text{aq})$	$\text{H}_2\text{SO}_4(\text{aq})$	$\text{CO}_3^{2-}(\text{aq})$	$\text{HCO}_3^-(\text{aq})$

19. a. $\text{H}_2\text{S}(\text{aq}) + \text{NH}_3(\text{aq}) \rightleftharpoons \text{HS}^-(\text{aq}) + \text{NH}_4^+(\text{aq})$
-
- acid base base acid





20. Textbook question 11:

- a. $\text{HCO}_3^{-}(\text{aq}) / \text{CO}_3^{2-}(\text{aq})$ and $\text{HS}^{-}(\text{aq}) / \text{S}^{2-}(\text{aq})$
 acid base acid base
- b. $\text{H}_2\text{CO}_3(\text{aq}) / \text{HCO}_3^{-}(\text{aq})$ and $\text{H}_2\text{O}(\text{l}) / \text{OH}^{-}(\text{aq})$
 acid base acid base
- c. $\text{HSO}_4^{-}(\text{aq}) / \text{SO}_4^{2-}(\text{aq})$ and $\text{H}_2\text{PO}_4^{-}(\text{aq}) / \text{HPO}_4^{2-}(\text{aq})$
 acid base acid base
- d. $\text{H}_2\text{O}(\text{l}) / \text{OH}^{-}(\text{aq})$ and $\text{H}_3\text{O}^{+}(\text{aq}) / \text{H}_2\text{O}(\text{l})$
 acid base acid base

Textbook question 12:

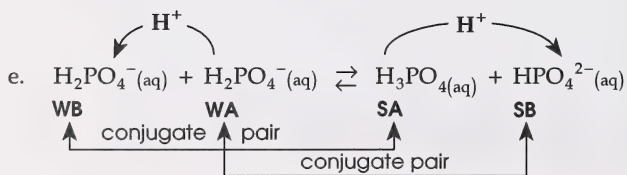
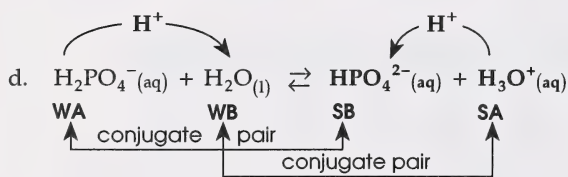
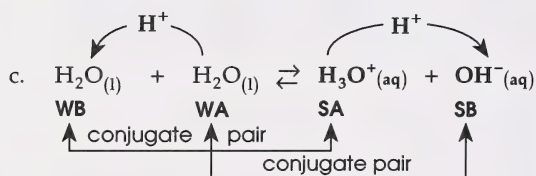
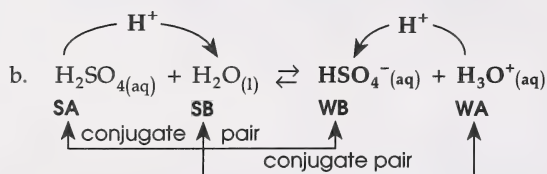
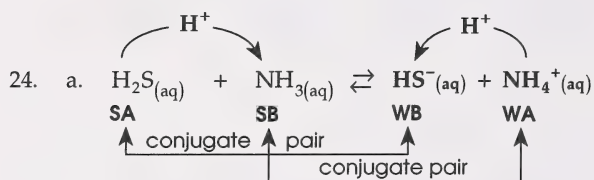
The two conjugate acid-base pairs for the hydrogen carbonate ion are $\text{HCO}_3^{-}(\text{aq}) / \text{CO}_3^{2-}(\text{aq})$ and $\text{H}_2\text{CO}_3(\text{aq}) / \text{HCO}_3^{-}(\text{aq})$.

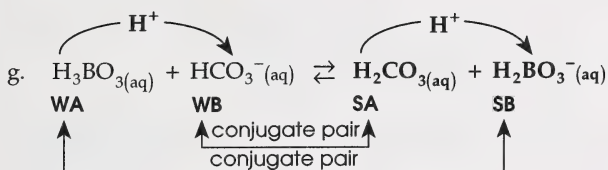
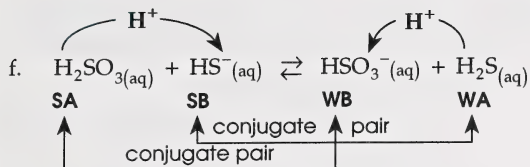
21.

Acid		Conjugate Base	
Stronger Acid	gives rise to	Weaker Conjugate Base	
decreasing strength of acid		decreasing strength of base	
Weaker Acid	gives rise to	Stronger Conjugate Base	

22. The sequence of acids from strongest to weakest is $\text{HClO}_4(\text{aq})$, $\text{HNO}_3(\text{aq})$, $\text{CH}_3\text{COOH}(\text{aq})$, $\text{HCO}_3^{-}(\text{aq})$.

23. The sequence of conjugate bases from strongest to weakest is $\text{CO}_3^{2-}(\text{aq})$, $\text{CH}_3\text{COO}^-(\text{aq})$, $\text{NO}_2^-(\text{aq})$, $\text{ClO}_4^-(\text{aq})$.





Section 2: Activity 2

1. An empirical generalization is sought that will allow accurate predictions.

2.

Redox Half-Reactions Table		Acids and Bases Table	
stronger OA	gives rise to	stronger acid	gives rise to
↓		↓	
weaker OA	gives rise to	weaker acid	gives rise to
↑		↑	
stronger RA		stronger conjugate base	
↑		↑	
weaker RA		weaker conjugate base	
↓		↓	
stronger OA		stronger acid	
↑		↑	
weaker OA		weaker acid	
↓		↓	
stronger RA		stronger conjugate base	

3.

Reaction Number	Percent Reaction (%)	Equilibrium Favours (reactants or products)	Relative Position of Reactants on Table of Acids and Bases
1	<50	reactants	base above acid
2	>99	products	acid above base
3	<50	reactants	base above acid
4	>50	products	acid above base
5	<50	reactants	base above acid
6	>99	products	acid above base

4. If the reactant acid appears above the reactant base (relative position) in the Acids and Bases table, the equilibrium will favour products. If the reactant acid appears below the reactant base on the Acids and Bases table, the equilibrium will favour reactants.
5. a. The acid is above the base – favours products. d. The acid is above the base – favours products.
 b. The acid is below the base – favours reactants. e. The acid is above the base – favours products.
 c. The acid is below the base – favours reactants.
6. The two ideas are the collision-reaction theory which explains how reactants meet, and the Brønsted-Lowry acid-base theory which suggests that a proton will transfer from an acid to a base.
7. Because an acid-base system is a competition for protons, it is most probable that the **strongest** acid will donate protons to the **strongest** base.

8. a.

PREDOMINANT SPECIES IN AQUEOUS SOLUTION	
Substance Dissolved	Predominant Species (Atoms, Ions, or Molecules)
high solubility ionic compounds	separate ions
strong acid	$\text{H}_3\text{O}^+(\text{aq})$, conjugate base
weak acids, soluble molecular compounds	molecules

b. The redox method and the acid-base method of listing predominant species are similar in the following ways:

- Strong acids and highly soluble ionic compounds are listed as separate ions.
- Weak acids or molecular compounds are listed as molecules.

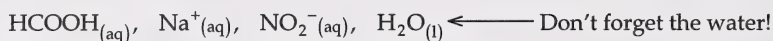
The two methods are different in the following way:

- The redox method lists stronger acids as $\text{H}^+(\text{aq})$ plus the conjugate negative ion. The acid-base method lists strong acids as $\text{H}_3\text{O}^+(\text{aq})$ plus the conjugate base because of the idea that the hydrogen ions react with water molecules to produce hydronium ions.

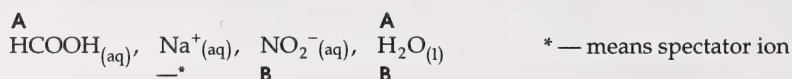
9. a. Methanoic acid ($\text{HCOOH}_{(\text{aq})}$) reacts with a sodium nitrite ($\text{NaNO}_{2(\text{aq})}$) solution.

Step 1

List all the species.

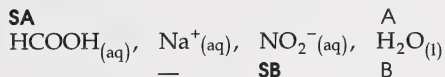
**Step 2**

Identify the acids and bases.

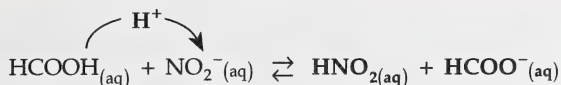


Step 3

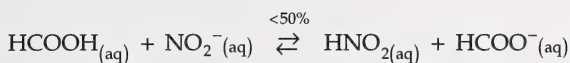
Using the table of acids and bases, identify the strongest acid (SA) and strongest base (SB).

**Step 4**

Transfer a proton from the SA to the SB and predict the products.

**Step 5**

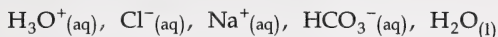
Use the generalization to predict the extent of the equilibrium. (Since $\text{HCOOH}_{(\text{aq})}$ is lower on the Acids and Bases table than $\text{NO}_2^-_{(\text{aq})}$, the reactants are favoured for this reaction equilibrium.)



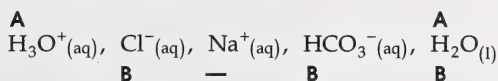
- b. A strong acid ($\text{HCl}_{(\text{aq})}$) reacts with a sodium bicarbonate solution ($\text{NaHCO}_{3(\text{aq})}$).

Step 1

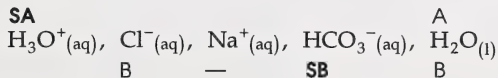
List all the species.

**Step 2**

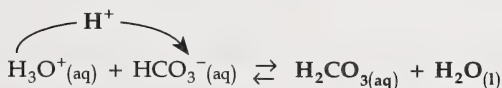
Identify the acids and bases.

**Step 3**

Identify the SA and SB.

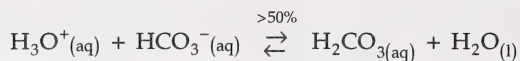
**Step 4**

Transfer a proton from the SA to the SB and predict the products.

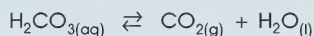


Step 5

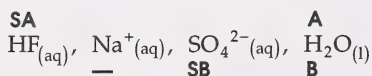
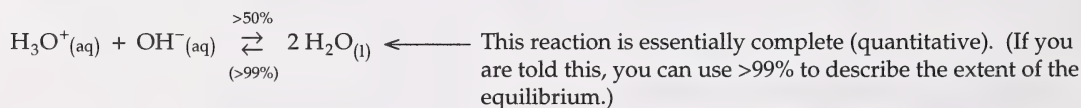
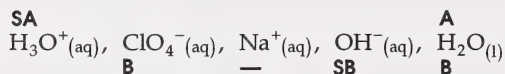
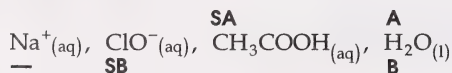
Use the generalization to predict the extent of the equilibrium. (Since $\text{H}_3\text{O}^+(\text{aq})$ is higher on the Acids and Bases table than $\text{HCO}_3^-(\text{aq})$, the products are favoured for this reaction equilibrium.)



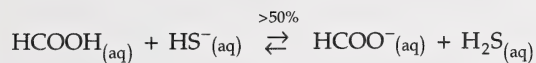
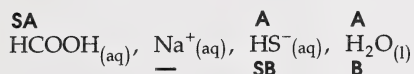
Note: You may be wondering why the question description said, *vigorous bubbling occurs*. When the product $\text{H}_2\text{CO}_{3(\text{aq})}$ is formed, it sets up its own equilibrium in water.



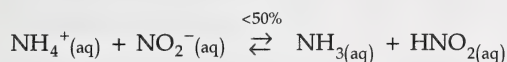
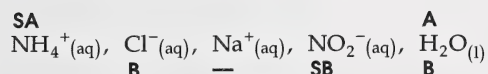
The bubbles ($\text{CO}_{2(\text{g})}$) are the same ones that form in carbonated beverages.

10. Textbook question 16:**Textbook question 17:****Textbook question 18:**

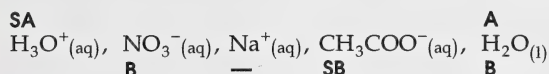
Textbook question 19:



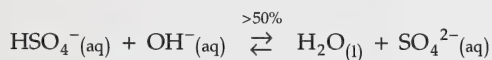
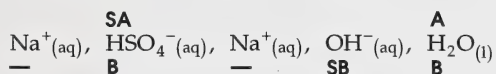
Textbook question 20:



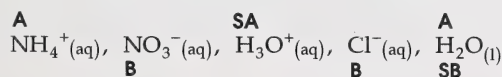
Textbook question 21:



Textbook question 22:



Textbook question 23:

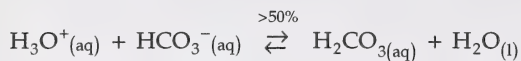
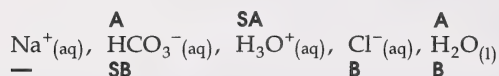


Ammonium nitrate cannot neutralize hydrochloric acid.

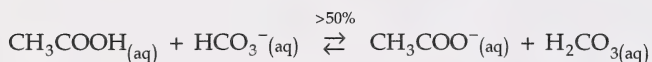
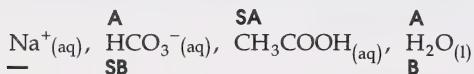
Section 2: Activity 3

1. The following are the predictions for each reaction:

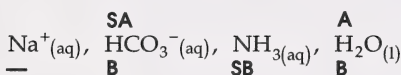
- Reaction 1 (reaction of $\text{NaHCO}_{3(aq)}$ with $\text{HCl}_{(aq)}$):



- Reaction 2 (reaction of $\text{NaHCO}_{3(aq)}$ with $\text{CH}_3\text{COOH}_{(aq)}$):

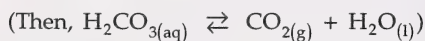


- Reaction 3 (reaction of $\text{NaHCO}_{3(aq)}$ with $\text{NH}_3_{(aq)}$):



2. The analysis is as follows:

- a. The reaction was $\text{H}_3\text{O}^+_{(aq)} + \text{HCO}_3^-_{(aq)} \rightleftharpoons \text{H}_2\text{CO}_{3(aq)} + \text{H}_2\text{O}_{(l)}$



Yes. The evidence suggests a vigorous reaction with the evolution of carbon dioxide gas, indicating the production of $\text{H}_2\text{CO}_{3(aq)}$. There is no evidence for the production of any other product.

- b. The increase in pH is evidence of the neutralization of $\text{HCl}_{(aq)}$.

- c. Yes. Again, the evidence indicates a reaction producing carbon dioxide gas, although there is no evidence for the production of the acetate ion.
- d. The disappearance of the odour of vinegar and the increase in pH is evidence of the conversion of acetic acid to product. It is reasonable to conclude that the equilibrium favours the products.
- e. There is no direct evidence of the products being formed.
- f. The fact that the ammonia smell remains indicates that the reaction is complete. This is consistent with the prediction of <50% completion using the five-step method. The decrease in pH indicates that some of the ammonia (a base) reacted.

3. The evaluation is as follows:

Although the evidence is somewhat limited, there is enough to conclude that the five-step method is an acceptable generalization. There was no evidence collected that directly falsified the predictions.

4. The predictions are as follows:

Predicted Reaction	Predicted Observations
1. $\text{NH}_4^+(\text{aq}) + \text{OH}^-(\text{aq}) \xrightleftharpoons{>50\%} \text{NH}_3(\text{aq}) + \text{H}_2\text{O}(\text{l})$	smell of ammonia
2. $\text{H}_3\text{O}^+(\text{aq}) + \text{CH}_3\text{COO}^-(\text{aq}) \xrightleftharpoons{>50\%} \text{H}_2\text{O}(\text{l}) + \text{CH}_3\text{COOH}(\text{aq})$	smell of vinegar
3. $\text{HSO}_4^-(\text{aq}) + \text{C}_6\text{H}_5\text{COO}^-(\text{aq}) \xrightleftharpoons{>50\%} \text{SO}_4^{2-}(\text{aq}) + \text{C}_6\text{H}_5\text{COOH}(\text{s})$	precipitate*
4. $\text{H}_3\text{O}^+(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons \text{H}_3\text{O}^+(\text{aq}) + \text{H}_2\text{O}(\text{l})$	no change in odour
5. $\text{H}_2\text{O}(\text{l}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons{<50\%} \text{OH}^-(\text{aq}) + \text{H}_3\text{O}^+(\text{aq})$	no litmus change
6. $\text{H}_2\text{O}(\text{l}) + \text{SO}_4^{2-}(\text{aq}) \rightleftharpoons{<50\%} \text{OH}^-(\text{aq}) + \text{HSO}_4^-(\text{aq})$	red litmus to blue
7. $\text{H}_2\text{O}(\text{l}) + \text{PO}_4^{3-}(\text{aq}) \rightleftharpoons{<50\%} \text{OH}^-(\text{aq}) + \text{HPO}_4^{2-}(\text{aq})$	red litmus to blue
8. $\text{HSO}_4^-(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightleftharpoons{<50\%} \text{SO}_4^{2-}(\text{aq}) + \text{H}_3\text{O}^+(\text{aq})$	blue litmus to red
9. $\text{H}_3\text{O}^+(\text{aq}) + \text{HCO}_3^-(\text{aq}) \xrightleftharpoons{>50\%} \text{H}_2\text{O}(\text{l}) + \text{H}_2\text{CO}_3(\text{aq})$	pH of solution increases
10. $\text{HCO}_3^-(\text{aq}) + \text{OH}^-(\text{aq}) \xrightleftharpoons{>50\%} \text{H}_2\text{O}(\text{l}) + \text{CO}_3^{2-}(\text{aq})$	pH of solution decreases
11. $\text{HSO}_4^-(\text{aq}) + \text{HCO}_3^-(\text{aq}) \xrightleftharpoons{>50\%} \text{SO}_4^{2-}(\text{aq}) + \text{H}_2\text{CO}_3(\text{aq})$	pH of solution increases

***Note:** You have no information on your solubility table to indicate that benzoic acid ($\text{C}_6\text{H}_5\text{COOH}(\text{aq})$) has low solubility. However, your textbook acid-base table has a note that indicates benzoic acid has a solubility of less than 0.10 mol/L.

5. A suggested procedure is as follows:

Reactions 1-4

- Add 2 mL-4 mL of each solution (about 1/3 of a test tube) to separate test tubes.
- Pour one solution into the other and note any evidence of a reaction. Record your results in a data table. (**Note:** Look for evidence of such things as odour change or precipitate formed.)

Reactions 5-11

- Add 5 mL-10 mL of the liquid to a beaker or flask.
- Test the liquid with litmus paper or a pH meter.
- Add a small quantity of solid and stir to dissolve.
- Test with litmus paper or a pH meter.
- Record your results in a data table.

6. Evidence will vary, but a suggested evidence table follows:

EVIDENCE TABLE

Reaction Number	Observations	Agreement with Prediction
1	odour of ammonia	yes
2	odour of vinegar	yes
3	white precipitate	yes
4	no change	yes
5	no change in litmus	yes
6	blue litmus turned red; solution turned cloudy	no
7	red litmus turned blue	yes
8	blue litmus turned red	yes
9	pH increases; gas bubbles	yes
10	pH increases	yes
11	pH increases; gas bubbles	yes

7. The experimental results of Reaction 6 (aluminum sulphate with water) disagreed with the prediction. However, the cloudy solution suggests the production of a precipitate, which could be aluminum hydroxide. This would explain the litmus paper turning red. Hydroxide ions would have been removed from solution in forming the precipitate, which would leave behind $\text{HSO}_4^-(\text{aq})$, an acid.
8. The results are not conclusive. The results of Reaction 6 failed to verify the prediction. However, for most purposes, the five-step method and the empirical generalization for determining the extent of reaction remains acceptable, since ten of eleven predictions were verified. The Brønsted-Lowry theory may have to be revised or restricted to somehow include discrepant events like Reaction 6.

9. The following inferences (conclusions) can be made, based on the evidence provided by the reaction equations given.

Reaction 1: $\text{CH}_3\text{COOH}_{(\text{aq})}$ is a stronger acid than $\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$.

Therefore, $\text{CH}_3\text{COOH}_{(\text{aq})}$
is
above
 $\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$

Reaction 2: $\text{HCOOH}_{(\text{aq})}$ is a stronger acid than $\text{CH}_3\text{COOH}_{(\text{aq})}$.

Therefore, $\text{HCOOH}_{(\text{aq})}$
is
above
 $\text{CH}_3\text{COOH}_{(\text{aq})}$
is
above
 $\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$

Reaction 4: $\text{C}_2\text{H}_5\text{COOH}_{(\text{aq})}$ is a weaker acid than $\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$.

Therefore, $\text{HCOOH}_{(\text{aq})}$
is
above
 $\text{CH}_3\text{COOH}_{(\text{aq})}$
is
above
 $\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$
is
above
 $\text{C}_2\text{H}_5\text{COOH}_{(\text{aq})}$

Note: The information given by Reaction 3 was inconclusive as it did not indicate a definite position of $\text{C}_2\text{H}_5\text{COOH}_{(\text{aq})}$.

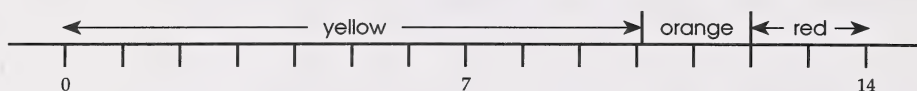
Acid		Conjugate Base	
SA ↓ WA	$\text{HCOOH}_{(\text{aq})}$	$\text{HCOO}^{-}(\text{aq})$	WB ↑ SB
	$\text{CH}_3\text{COOH}_{(\text{aq})}$	$\text{CH}_3\text{COO}^{-}(\text{aq})$	
	$\text{C}_3\text{H}_7\text{COOH}_{(\text{aq})}$	$\text{C}_3\text{H}_7\text{COO}^{-}(\text{aq})$	
	$\text{C}_2\text{H}_5\text{COOH}_{(\text{aq})}$	$\text{C}_2\text{H}_5\text{COO}^{-}(\text{aq})$	

Section 2: Activity 4

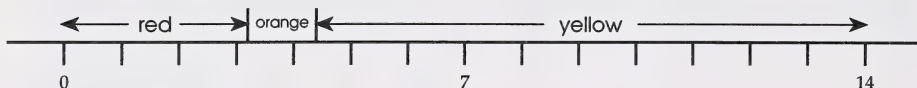
1. Acid-base indicators are substances that **change colour when reacted with acids or bases**.

Indicator	Colour 1	Colour 2
litmus	red	blue
phenolphthalein	colourless	red (pink)

3. a. alizarin yellow R: colour change range 10.1 – 12.0



b. methyl orange: colour change range 3.2 – 4.4



4. The predominant colour in the colour change range of indigo carmine is green (blue + yellow → green).

5. Thymolphthalein is blue at a pH of 12.8 (pH > 10.6 → blue).

$$\begin{aligned}
 \text{pH} &= -\log[\text{H}^+(\text{aq})] \\
 &= -\log(1.58 \times 10^{-6}) \\
 &= 5.801
 \end{aligned}$$

Since chlorophenol red undergoes a colour change when the pH is 5.801 (colour change range is pH 5.2–6.8), chlorophenol red is orange in a solution of $[\text{H}^+(\text{aq})] = 1.58 \times 10^{-6} \text{ mol/L}$.

7. Textbook question 13:

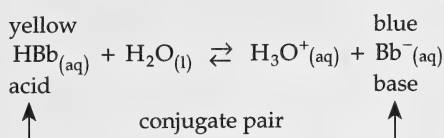
- | | |
|------------------------------------|------------------------------------|
| a. The indicator colour is red. | c. The indicator colour is blue. |
| b. The indicator colour is yellow. | d. The indicator colour is orange. |

Textbook question 14:

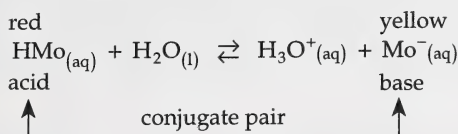
- | | |
|--|--|
| a. The solution pH is less than 4.8. | c. The solution pH is greater than 5.4. |
| b. The solution pH is greater than 12.0. | d. The solution pH is between 6.0 and 7.6. |

8. An indicator is a **conjugate weak acid-base pair** formed when an indicator dye dissolves in water.

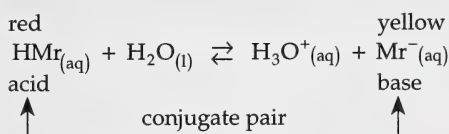
9. a. bromothymol blue



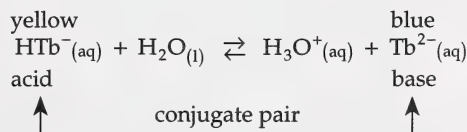
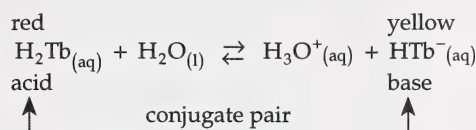
b. methyl orange



c. methyl red



d. thymol blue



10. False. The ability to change colour is a prerequisite to being an indicator.

11. a. In strong acid solution, the hydronium ion concentration is very high. A high hydronium ion concentration will shift the equilibrium towards the reactant side of the $\text{HIn}_{(\text{aq})} - \text{In}^-_{(\text{aq})}$ system.

b. The predominant indicator species would be $\text{HIn}_{(\text{aq})}$ at high hydronium ion concentrations, so the solution colour would be yellow.

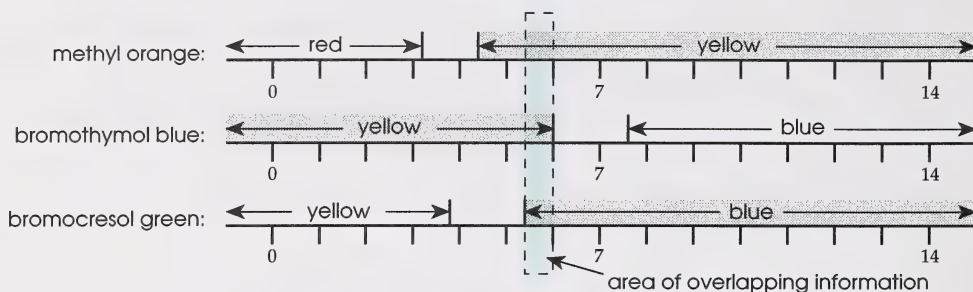


d. The addition of hydroxide ions effectively removes hydronium ions from the product side of the equilibrium. The system will shift to the right (towards the products) in response. The predominant indicator species would become the $\text{In}^-_{(\text{aq})}$ ion and the solution would be blue.

12. Textbook question 15:

a. The inferences, based on the information given, are as follows:

- methyl orange turning yellow $\xrightarrow{\text{means}}$ pH > 4.4
- bromothymol blue turning yellow $\xrightarrow{\text{means}}$ pH < 6.0
- bromocresol green turning blue $\xrightarrow{\text{means}}$ pH > 5.4



The pH range that is common to all three indicators (the overlap area) tells you the approximate pH of the solution: pH = 5.4-6.0.

b. The approximate hydronium ion concentration is as follows:

$$\begin{aligned}
 [\text{H}_3\text{O}^+(\text{aq})] &= [\text{H}^+(\text{aq})] \\
 &= 10^{-\text{pH}} \\
 &= 10^{-5.4} \text{ to } 10^{-6.0} \\
 &= 4 \times 10^{-6} \text{ mol/L to } 1 \times 10^{-6} \text{ mol/L}
 \end{aligned}$$

- Indicators (HIn) that change colour at low pH values do so because they are stronger acids. As stronger acids they have **weaker** H – In bonds. They donate their protons **easily** to the added base since they can compete effectively with the hydronium ion to donate protons. This occurs at **lower** pH values. Indicators whose colour change range occurs at higher pH values are **weaker** acids with **stronger** H – In bonds. The proton donation and subsequent colour change take place at higher $\text{OH}^-(\text{aq})$ concentrations and therefore at higher pH values.
- The three indicators listed among the acids (from strongest to weakest) are methyl orange, bromothymol blue, and phenolphthalein. The indicator colour chart doubles as a table of acid-base strengths dedicated specifically to indicators.
- $\text{HX}_{(\text{aq})}$ is a stronger acid than $\text{HY}_{(\text{aq})}$.
- pH test strips can be used to test the pH of swimming pool and aquarium water.

17. The following is a set of sample evidence:

Indicator	Solution A Colours	Indicator	Solution B Colours	Indicator	Solution C Colours
methyl violet	blue	indigo carmine	blue	phenolphthalein	colourless
methyl orange	yellow	phenol red	yellow	thymol blue	yellow
methyl red	red	bromocresol green	blue	bromocresol green	yellow
phenolphthalein	colourless	methyl red	yellow	methyl orange	orange

18. The following is a sample analysis table:

SOLUTION A			SOLUTION B			SOLUTION C		
Indicator	Colour	pH	Indicator	Colour	pH	Indicator	Colour	pH
Mv ⁻	blue	>1.6	Hlc	blue	<11.4	HPh	colourless	<8.2
Mo ⁻	yellow	>4.4	HPr	yellow	<6.6	HTb ⁻	yellow	2.8 – 8.0
HMr	red	<4.8	Bg ⁻	blue	>5.4	HBg	yellow	<3.8
HPh	colourless	<8.2	Mr ⁻	yellow	>6.0	HMo	orange	3.2 – 4.4
Solution pH = 4.4 – 4.8			Solution pH = 6.0 – 6.6			Solution pH = 3.2 – 3.8		

19. • Based on the indicators and their colours in the solution, the pH could be estimated as follows:

Indicator	Colour of the Indicator in the Solution	pH
methyl orange	yellow	>4.4
methyl red	yellow	>6.0
bromothymol blue	blue	>7.6
phenolphthalein	colourless	<8.2

- Based on the information gathered, the solution pH is between 7.6 and 8.2. To the nearest whole number the pH would be 8.

Section 2: Follow-up Activities

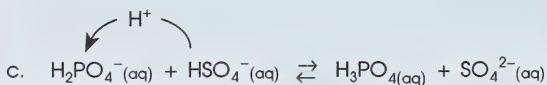
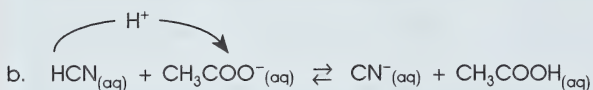
Extra Help

1.

I. Definitions

Acid – **substance that donates protons**example **any substance from left column in the Acids and Bases table**Base – **substance that accepts protons**example **any substance from right column in the Acids and Bases table**

II. Proton Transfer

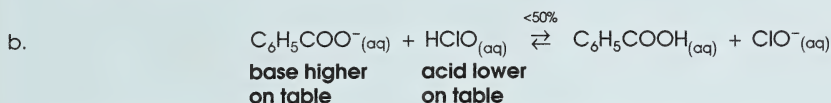
a. Protons transfer from **acids** to **bases**.

III. Concept of Weak and Strong

Strong acid – **weak attraction for protons; donates protons readily**example – $\text{HCl}_{(\text{aq})}$ Weak acid – **strong attraction for protons; donates protons less readily**example – $\text{CH}_3\text{COOH}_{(\text{aq})}$ Strong base – **strong attraction for protons; accepts protons readily**example – $\text{OH}^{-}_{(\text{aq})}$ Weak base – **weak attraction for protons; accepts protons less readily**example – $\text{SO}_4^{2-}_{(\text{aq})}$

IV. Predicting Extent of Reaction

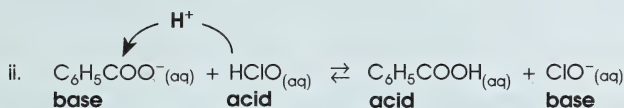
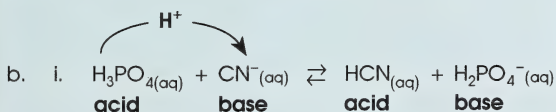
- a. The equilibrium generalization says that if the reactant acid is **higher** than the reactant base on the Acids and Bases table, equilibrium will favour products. If the reactant acid is lower than the reactant base, equilibrium will favour **reactants**.



Since the acid is lower on the table than the base, **reactants are favoured**.

V. Neutralization

- a. $\text{ACID} + \text{BASE} \rightleftharpoons \text{ACID} + \text{BASE}$

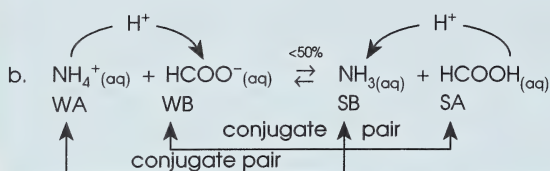
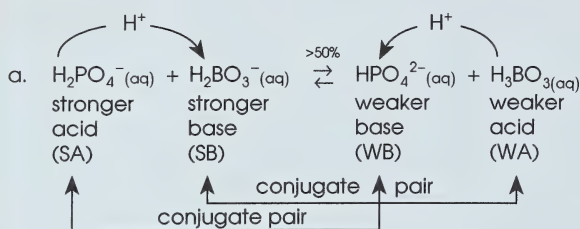


VI. Conjugate Pairs – What Are They?

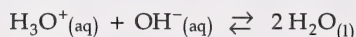
In any conjugate pair, one member of the pair is an **acid** and the other member of the pair is a **base**. They differ by only one **proton**. An acid on the reactant side becomes a **base** on the product side. A base on the reactant side becomes an **acid** on the product side. If an acid is strong, its conjugate base is **weak**. If an acid is weak, its conjugate base is **strong**.

VII. Putting It All Together

The analysis of the two systems is as follows:



2. The main reason the Brønsted-Lowry theory is not considered comprehensive is that it fails on its own to predict some acid-base behaviour. With the aid of two empirical generalizations which have no direct connection with the theory, the predictive power of the theory increases somewhat, but it is still not what scientists call a truly comprehensive theory.
3.
 - a. Only indicators change colour as they donate the proton.
 - b. Congo red would be red in colour at pH = 6.
4.
 - a. In a strong acid solution, this indicator would be the colour **red**.
 - b. In a strong base solution, this indicator would be the colour **yellow**.
 - c. The indicator colour in the colour change range would be orange.
 - d. The addition of $\text{NaOH}_{(\text{aq})}$ or any ionic hydroxide compound would react with $\text{H}_3\text{O}^+_{(\text{aq})}$ ions in the solution, causing the equilibrium to shift to the right.



- e. With a colour change range at such a high pH, $\text{HIn}_{(\text{aq})}$ is a relatively weak indicator acid. Its conjugate base $(\text{In}^-_{(\text{aq})})$ is relatively strong.

5. The acidity or basicity of the two solutions may be determined as follows:

Solution A

- orange IV → yellow means pH >2.8
- phenolphthalein → pink means pH >8.2
- bromothymol blue → blue means pH >7.6

Therefore, Solution A is basic.

Solution B

- orange IV → yellow means pH >2.8
- phenolphthalein → colourless means pH <8.2
- bromothymol blue → yellow means pH <6.0

Therefore, Solution B is acidic.

Enrichment

1. A universal indicator is a combination of several indicators of various strengths. Over the span of the pH scale, these indicators, in turn, change colours to indicate the various pH values as they are reached.

The universal indicator described in the video Acid-Base Indicators is a combination of the following four indicators.

- methyl orange (HMo) $K_a = 10^{-4}$ mol/L
- methyl red (HMr) $K_a = 10^{-5}$ mol/L
- bromothymol blue (HBb) $K_a = 10^{-7}$ mol/L
- phenolphthalein (HPh) $K_a = 10^{-9}$ mol/L

The K_a values of the indicators give you an idea of the indicators' relative strengths and the order in which they would change colour in solutions of varying pH values. The indicator colour in solution at any one time is a combination of the four indicator colours.

2. a. The calculated pH values of each of the acids are as follows:

- pH of $\text{HF}_{(\text{aq})}$ (Solution A) = 2.09
- pH of $\text{HCN}_{(\text{aq})}$ (Solution B) = 5.10
- pH of $\text{CH}_3\text{COOH}_{(\text{aq})}$ (Solution C) = 2.87
- pH of $\text{HBr}_{(\text{aq})}$ (Solution D) = 1.00

example calculation for $\text{HF}_{(\text{aq})}$:

$$K_a = \frac{[\text{H}_3\text{O}^+_{(\text{aq})}]^2}{[\text{HF}_{(\text{aq})}]}$$

$$\begin{aligned} [\text{H}_3\text{O}^+_{(\text{aq})}] &= \sqrt{(6.6 \times 10^{-4} \text{ mol/L})(0.10 \text{ mol/L})} \\ &= 8.124 \times 10^{-3} \text{ mol/L} \\ &= 8.1 \times 10^{-3} \text{ mol/L} \end{aligned}$$

$$\begin{aligned} \text{pH} &= -\log(8.124 \times 10^{-3}) \\ &= 2.09 \end{aligned}$$

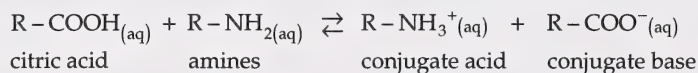
- b. A data table with predicted evidence should look as follows:

Indicator	Unknown Solutions			
	A	B	C	D
orange IV	orange	yellow	yellow	red
methyl orange	red	yellow	red	red

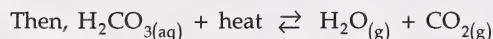
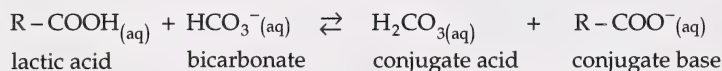
- c. Comparing the specific colours of the unknowns on the data table to the colour each acid would exhibit at their calculated pH,

- Only the solution with a pH of 2.09 can exhibit the orange/red indicator colour combination. Solution A must be $\text{HF}_{(\text{aq})}$.
- Only the solution with a pH of 5.10 can exhibit the yellow/yellow indicator colour combination. Solution B must be $\text{HCN}_{(\text{aq})}$.
- Only the solution with a pH of 2.87 can exhibit the yellow/red indicator colour combination. Solution C must be $\text{CH}_3\text{COOH}_{(\text{aq})}$.
- Only the solution with a pH of 1.00 can exhibit the red colour in both indicators. Solution D must be $\text{HBr}_{(\text{aq})}$.

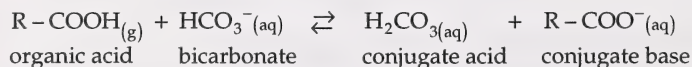
3. a. Lemon juice is 5%-8% citric acid. The cause of the fishy odour in fish is the presence of organic bases called amines. Lemon juice neutralizes the amines, reducing the fishy smell.



- b. Buttermilk contains lactic acid. Lactic acid, in combination with baking soda ($\text{NaHCO}_{3(\text{s})}$) or baking powder (a mixture of sodium bicarbonate and calcium hydrogen phosphate, $\text{CaHPO}_{4(\text{s})}$) reacts to produce $\text{H}_2\text{CO}_{3(\text{aq})}$, which, at the high temperature of an oven, decomposes readily to produce water vapour and carbon dioxide gas. The carbon dioxide gas expands into the gluten fibers of the batter, causing the pancakes to rise.

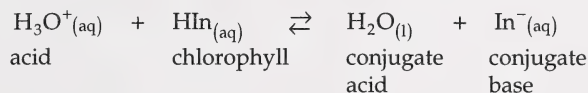


- c. Many of the by-products of food spoilage by bacteria are organic acids, most of which have an unpleasant smell. The sodium bicarbonate acts as a base, neutralizing the organic acids.

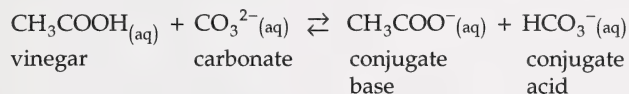


- d. Vinegar, an acid, can react with any leavening agent (a base) in a reaction like the one given in answer b.

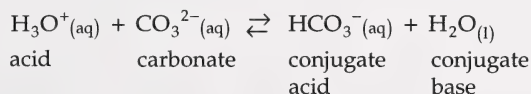
- e. If the water in which the vegetables are cooked is acidic, the water will react with the green chlorophyll in an indicator-like reaction, decolourizing the chlorophyll.

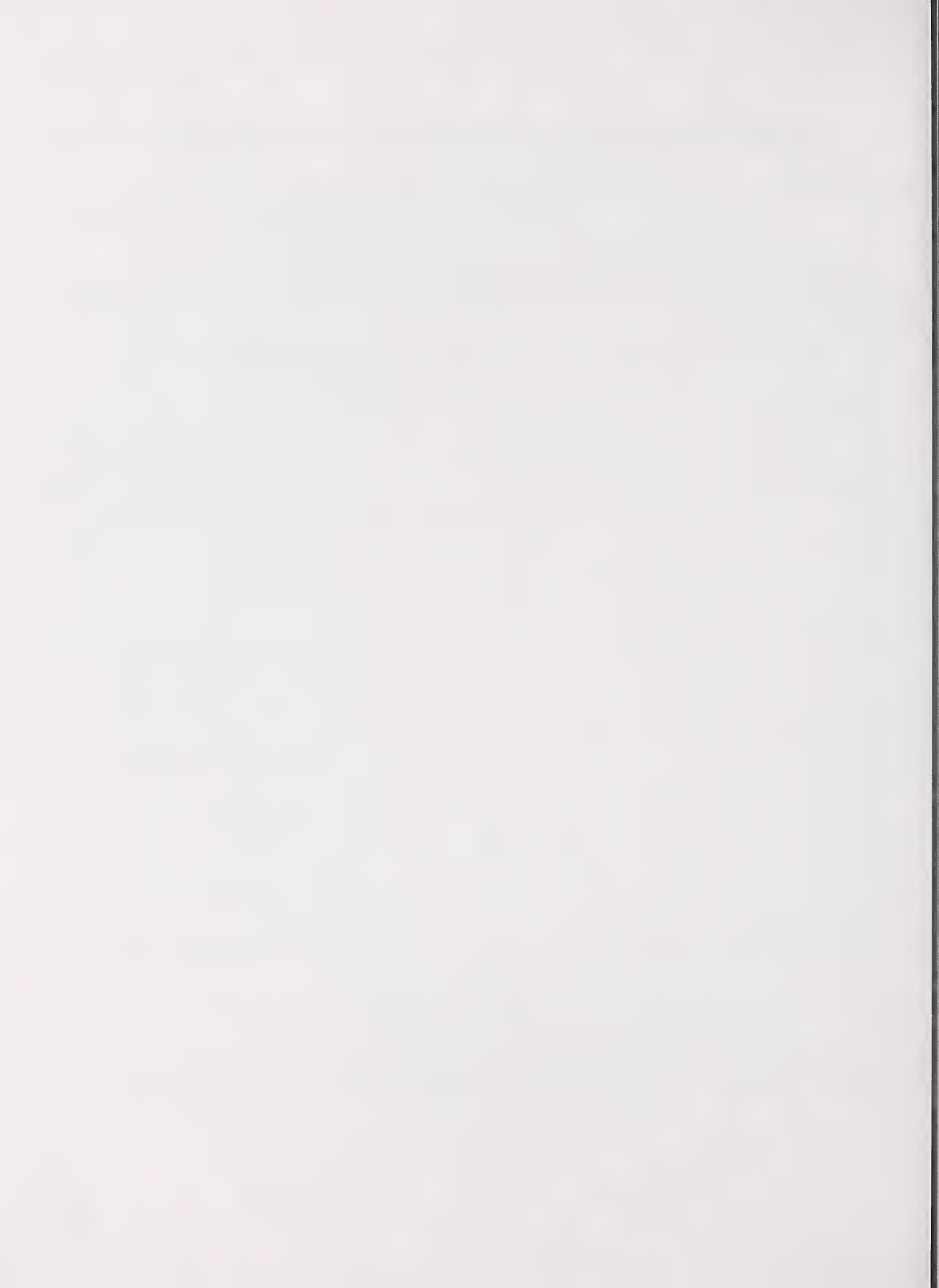


- f. The scale on kettles and pots is a mixture of calcium and magnesium carbonates (bases) which is not very soluble in water. The vinegar reacts with the carbonate ions.



- g. Marble contains many solid carbonate salts. Any acid-based cleaner will react with the carbonate in the marble, ruining the marble's surface.





NOTES

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